# FEASIBILITY OF FILAMENT WINDING
## LARGE SHIP HULLS

for
Naval Research Laboratory
Washington, D.C.
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by
J. L. McLarty
McClean-Anderson Laboratories
Menomonee Falls, Wisconsin

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

During this study effort, the Contractor analyzed the feasibility of placing fibers on a hull-shaped mandrel in such a way as to (1) cover the mandrel with fibers at a variety of angles, and (2) yield a structure conforming to the contours of the mandrel. After suitable fiber placements were found to be feasible, the feasibility was verified by winding a 1/48-scale hull-shaped model. Thickness specifications for a full size filament wound hull were then developed, and the Contractor wound small sections of (next page)

20.    ABSTRACT (continued)

such a hull to demonstrate that structures of the specified thick-
ness could be wound satisfactorily.    Finally, the Contractor
analyzed whether the winding trials carried out during the study
adequately demonstrated the feasibility of winding ship hulls of
200-foot length.    This report introduces the developments that led
to the study, describes the windings and analyses performed during
the study, and presents conclusions and recommendations for further
study.

## TABLE OF CONTENTS

# LIST OF ILLUSTRATIONS

# FOREWORD AND ACKNOWLEDGEMENTS

This report deals with an efficient, non-labor-intensive fabrication process that is of significant strategic value because it promises to increase the Navy's surge capacity and maneuver warfare capabilities; i.e., the capability to greatly increase production on short notice in times of emergency.

1

SUMMARY

## SUBJECT DEFINITION

Filament winding is a fabrication method whereby continuous, resin-impregnated fibers are wound onto a revolving three-dimensional form known as a mandrel (see Figure 1). When the resin cures, the result is a strong, light-weight structure with contours resembling those of the mandrel.

## CONCLUSIONS

This report concludes that it is feasible to produce ship hulls of 200-foot length by the filament winding process. The advantages of producing ships by the filament winding process are as follows:

## ADVANTAGES

- Filament wound ships should exhibit higher strength-to-weight ratios and greater fatigue resistance than steel ships. In addition, they are inherently capable of escaping detection by metal sensing devices. Their simple, reliable, and maintainable design enhances their usefulness for maneuver warfare and other strategic purposes.

- The filament winding process utilizes low-cost, readily available glass fibers and plastic resins. The resins can be produced from petroleum, gas, or coal. Both materials can be produced with less energy than that
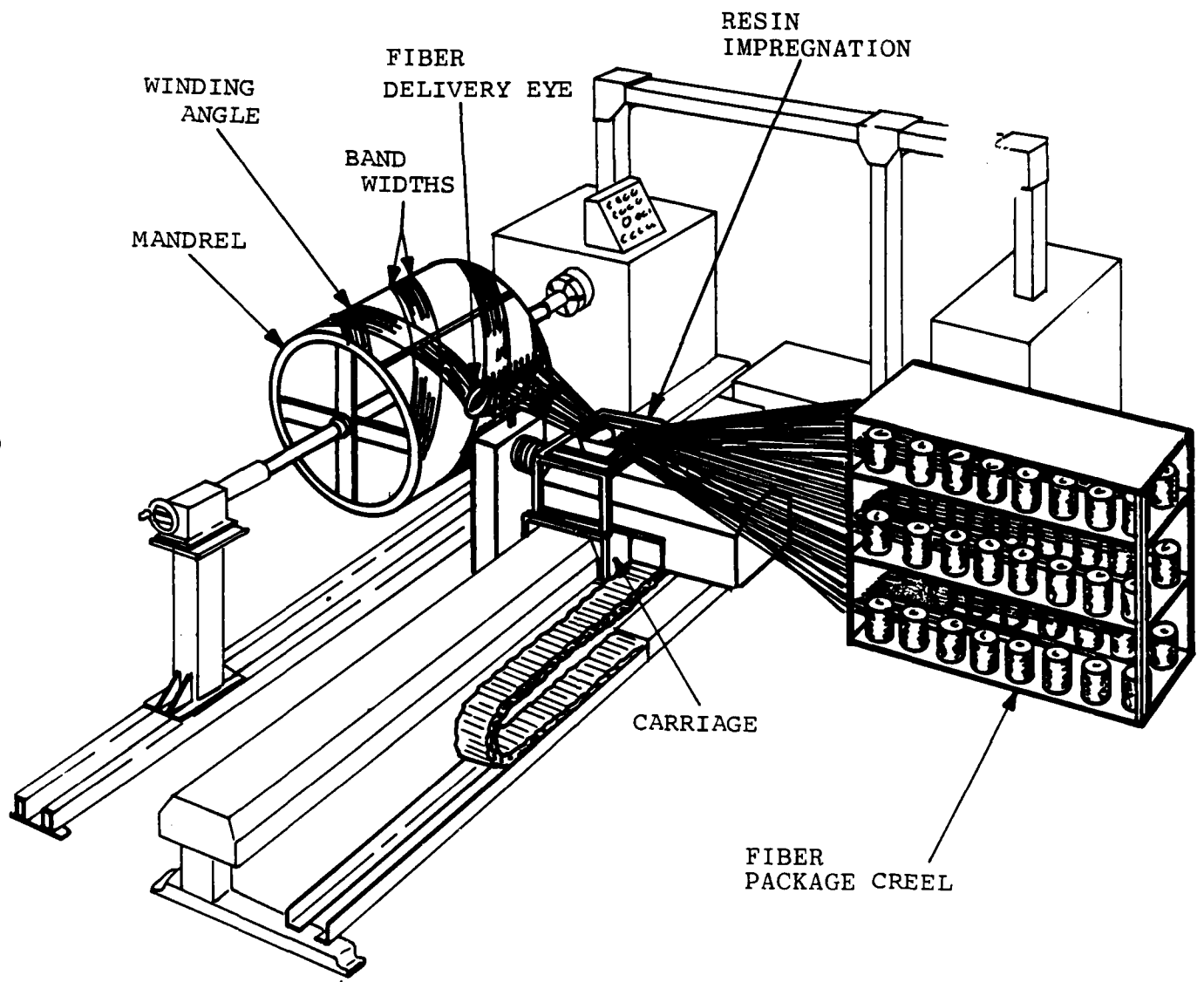
Figure 1.    Typical Filament Winding Machine

3

required for the production of aluminum or steel.

- The filament winding process is highly automated and efficient. It is estimated that crews of six to ten men per shift could wind a 200-foot-long hull in less than two days. Set-up would require an additional one to four days, as would final fitting and trimming of the finished hull.

- The materials and equipment involved can withstand long periods of storage with minimal maintenance. Start-up could be accomplished in a matter of days by one or two trained personnel, assisted by unskilled laborers. Switching from the production of one type of hull to production of a completely different null could be accomplished in a similar amount of time with a similar staff.

The conclusion that it is feasible to filament wind 200-foot-long ship hulls (similar to the model shown in Figure 2) is supported by the positive resolution of the following three critical issues:

## CRITICAL ISSUES

The first issue is whether fibers can be placed on a hull-shaped mandrel in such a way as to (1) cover the mandrel with fibers at a variety of angles, and (2) yield a structure conforming to the contours of the mandrel. This issue is basic to the filament winding process. If a mandrel cannot be covered with fibers, the resulting structure will not be complete; if fibers cannot be placed

4
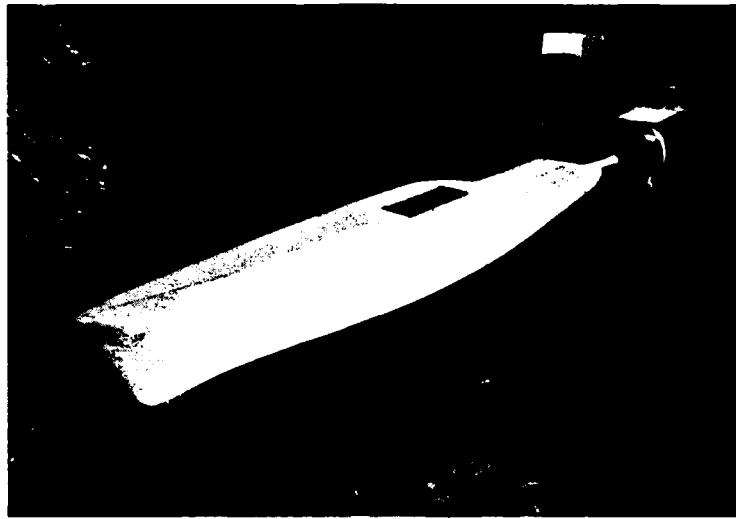
Figure 2.    1/48-Scale Model of 200-foot Ship Hull

on the mandrel at a variety of angles, the structure will not be
strong in all directions; and, finally, if fibers cannot be
placed and remain on the mandrel so as to conform to the contours
of the mandrel, then the structure will not resemble the mandrel.
The successful placement of fibers on a hull-shaped mandrel was
determined experimentally (see Figure 3).    The fiber placements
achieved during manual and automatic winding trials were recorded
in chart form and demonstrated during the actual production of a
1/48-scale ship hull.

The second issue is whether structures of the thickness required
for a ship hull of 200-foot length can be wound successfully.  This
issue is basic to the production of large filament wound structures.
Without walls of adequate thickness and strength, such a structure
would be useless.    The successful winding of walls of the required
thickness was demonstrated by producing three-inch thick sections of
a full sized hull wall (see Figure 4).
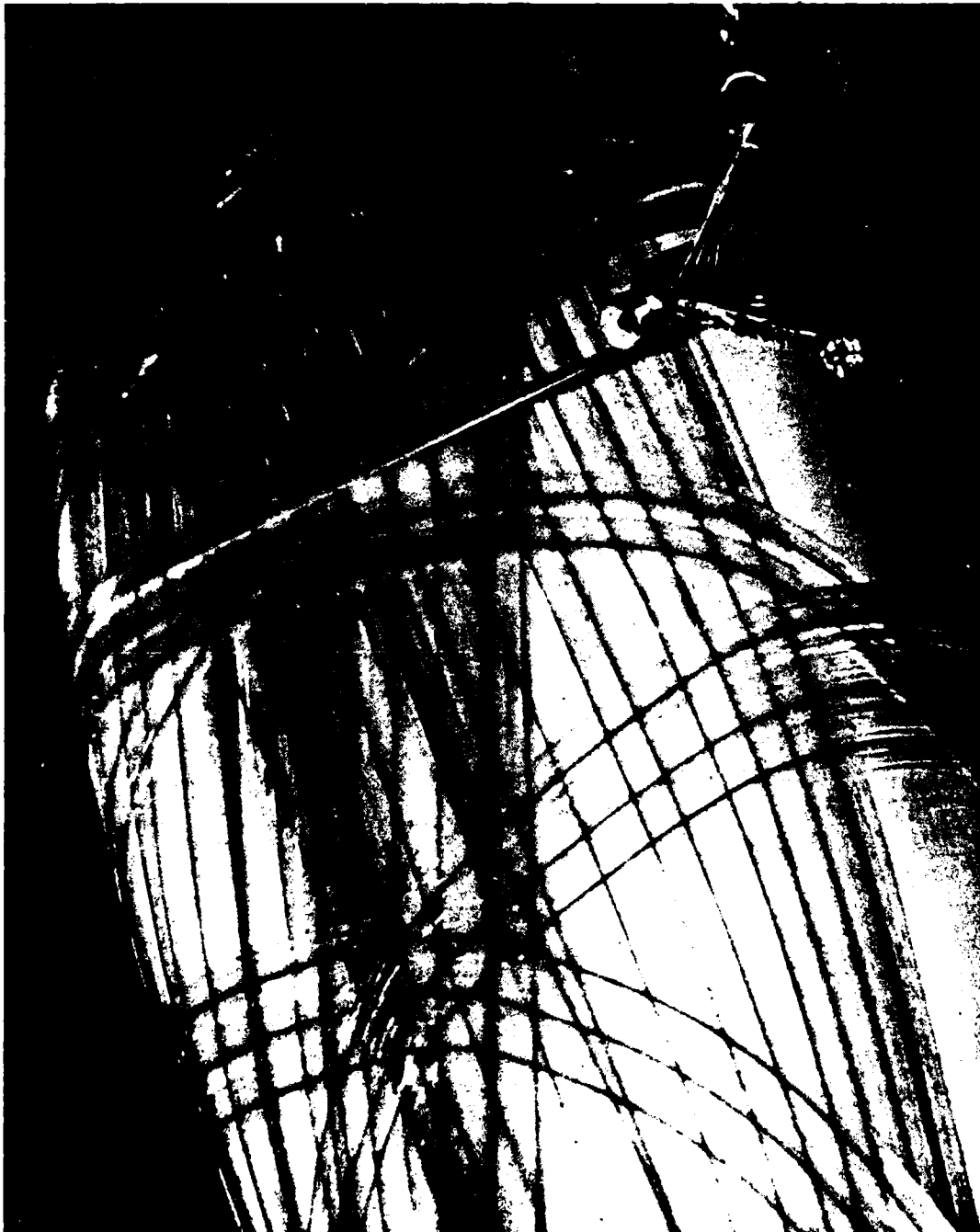
Figure 3. Placing Fibers on Hull Mandrel

6

Figure 4.   Section of Thick Hull Winding

The third issue is whether the winding procedure followed during
the study can be considered to adequately demonstrate the feasi-
bility of winding a 200-foot long ship hull.   This issue was sub-
jected to careful analysis by experienced engineers who are thoroughly
familiar with the filament winding process.   They concluded that
the winding of a 200-foot-long hull would differ in four respects
from the windings carried out during the study.   They are discussed
in Section V.   None of the differences cast doubt upon the preliminary
ary findings of the study, or raised any new issues of feasibility.

## RECOMMENDATION

This report recommends the design and fabrication of a 30-foot-long
ship model, followed by fabrication of a full size section, so that
winding machinery and structural elements of the hull can be demon-
strated for the Navy before commitment to filament winding a full
size hull.   See Figures 5A and 5B.
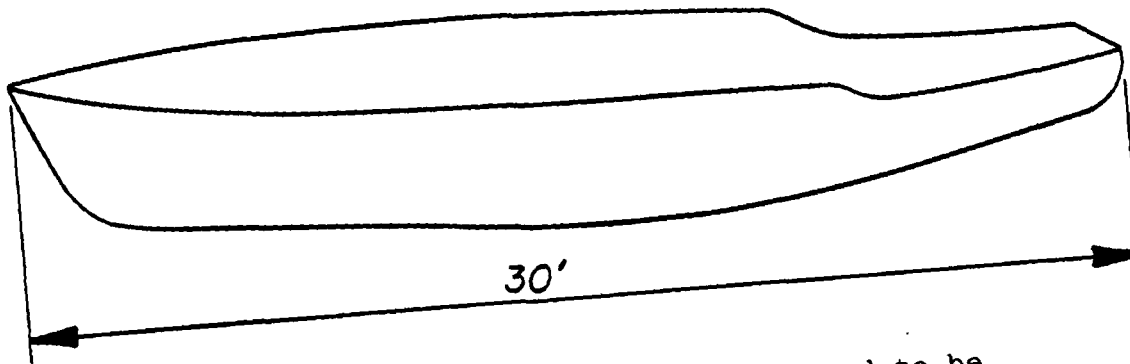
Figure 5A.    30-ft Ship Hull Proposed to be Filament Wound
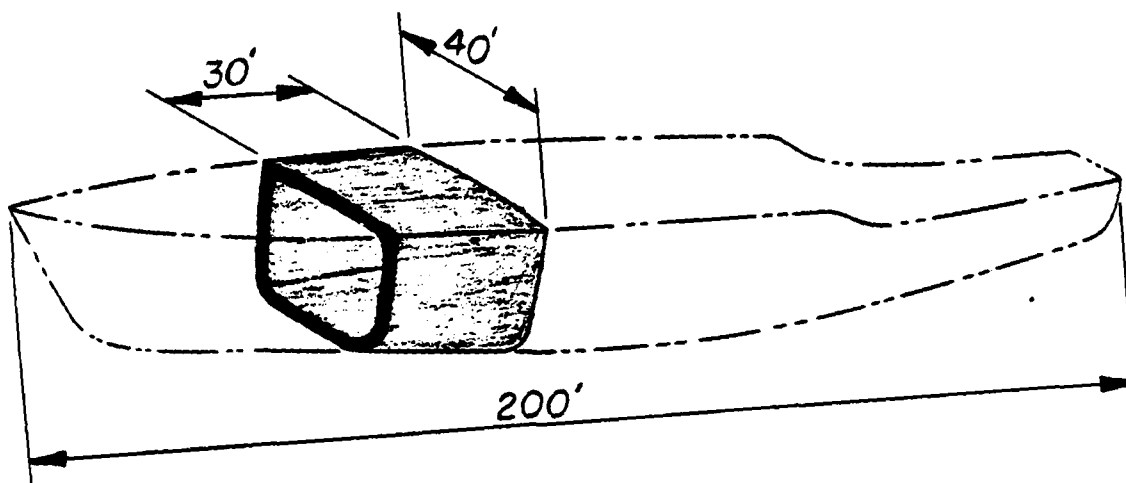


Figure 5B.    Section of Full Size Hull Proposed to be Filament Wound

8

# SECTION 1

## INTRODUCTION

### 1.1  Scope

This introductory section is further divided into three sub-sections devoted to the following topics:

- Section 1.2 describes the strategic benefits that prompted the Navy to study the feasibility of filament winding large ship hulls.

- Section 1.3 summarizes the technological development of the filament winding process--one of the most promising methods for achieving rapid fabrication of fiber-reinforced, or "composite," structures up to and beyond 200 feet in length.

- Section 1.4 discusses the objectives of the feasibility study introduced herein.

### 1.2  Strategic Benefits of Filament Winding Large Ship Hulls

The strategic value of fiber-reinforced (or "composite") structures is based upon their high strength-to-weight ratios and their non-metallic, non-magnetic physical properties.  Additional value is derived from the low cost and ready availability of fibers and resins.

9

Despite these advantages, the fabrication of large composite structures has been limited by a lack of suitable fabrication methods. While large, complex structures can be manufactured by the manual application of fibers and resin, the process is costly and labor-intensive. The limitations of manual fabrication methods has not, however, prevented the fabrication of composite ship hulls by foreign governments.

Since a number of naval applications, including mine-sweeping, require non-metallic ship hulls, the Navy has closely observed international efforts to fabricate composite hulls. In addition, it has monitored with considerable interest the state of the art in the filament winding process and other fabrication methods.

## 1.3 Technological Development of the Filament Winding Process

1.3.1 Description of the Filament Winding Process

Filament winding is a fabrication method whereby continuous, resin-impregnated fibers are wound on a revolving, three-dimensional form known as a mandrel (see Figure 1). When the resin cures, a strong, light-weight composite structure with contours resembling those of the mandrel is produced.

Mandrels utilized in the filament winding process are often designed for ease of removal from the cured winding. In some cases, however, mandrels are designed to remain in place as an integral part of the completed structure.

A typical filament winding machine has a headstock and a tail-stock in which the mandrel can be securely chucked.  As the mandrel revolves, filaments are drawn from spools through a "delivery eye" to the mandrel.  Along the way, the filaments travel through a resin bath which coats them with a controlled amount of resin (see Figure 1).

Throughout the winding process, the filament delivery eye travels back and forth between the machine's headstock and tailstock. This travel causes fibers to be wound along a specific path on the mandrel surface in accordance with precise trigonometric and topological formulas.  Varying the relationship between mandrel revolutions and delivery eye travel alters the fiber path and affects the nature and extent of surface coverage achieved by the winding process.

1.3.2  Traditional Advantages of the Filament Winding Process

Traditionally, the filament winding process has offered the following advantages when compared with other methods for fabricating composite structures:

- It utilizes fibers in their lowest cost form.  They need not be woven, chopped, or prepared in any way.
- It accomplishes the coating and placement of fibers automatically, with as little as ten percent of the manpower required by other methods.
- It places fibers on the mandrel surface with unsurpassed accuracy and repeatability.  The inadvertent gaps and overlaps associated with other method are eliminated.

11

- It places fibers at virtually any desired angle with re-
  spect to the longitudinal axis of the mandrel, thereby
  affording selection of fiber paths offering maximum strength
  and minimum material usage.

- It permits wall thicknesses to be varied according to need
  by controlling the number of fiber layers applied in any
  given location on the mandrel surface.

- It requires a small investment in machinery relative to the
  savings in materials and production time provided by the
  process.    In a production setting, the machinery pays for
  itself in a very short time.

1.3.3  New Capabilities of the Filament Winding Process

The production of computer-controlled filament winding machines in
the late 1970's greatly expanded the capabilities of the filament
winding process.    The refinement of filament delivery systems
throughout the 1970's had a similar impact on process capabilities.
As a result of these developments, the filament winding process
now offers the following advantages, in addition to those item-
ized above.

- Irregular shapes that require highly variable movements
  of the filament delivery system can be wound with relative
  ease.    Computer-assisted winding has eliminated the need
  for complex mathematical calculations.    Set-up require-
  ments have been reduced to a minimum.

- The time required for winding large structures has been
  reduced as filament delivery systems have increased in

12

capacity. Presently, filaments and resin can be deliver-
ed in precise proportions at rates in excess of 40,000 lbs/
hr. At these rates, even very large structures can be
wound in a matter of days.

- The application of mat, cloth, foam, or other materials to
  the mandrel surface can be coordinated by computer during
  the winding process. The selective application of such
  materials makes it possible to vary the thickness, density,
  configuration, and other physical properties of all or any
  part of the finished structure.

1.3.4 Successful Applications of the Filament Winding Process
Currently, machines capable of winding relatively large structures
are employed in a number of industrial applications. The winding
of thick-wall laminates--once considered impractical--is also being
carried out successfully. The following examples are among the
most noteworthy successes known to the author of this report.

- Several years ago, Fabricated Plastics, Ltd., of Canada
  wound exhaust stack sections measuring 22 feet in dia-
  meter by 45 feet in length. The winding process took
  only 17 hours and required just three men. (The produc-
  tion methods previously employed by the company required
  the efforts of nine men over the course of three weeks.)
  In addition to requiring less time and labor, the fila-
  ment wound sections required less material and exhibited
  more uniform quality than sections previously produced
  by other methods.

13

- In 1975 a railroad hopper car, measuring 13 feet in depth and 65 feet in length, was filament wound on a steel mandrel manufactured at a shipyard. Despite the irregular pear-shaped cross-section, the mandrel was successfully wound with efficient use of material and a uniformly high level of quality.

- Automotive leaf springs up to 1-1/4 inches thick were successfully wound in 1979, yielding fatigue limits and mechanical strengths equal to or greater than those exhibited by thin-walled structures. A progressive in-process curing was used. This accomplishment indicates that existing winding technology can be used to produce thick-walled laminates with the physical properties required for extremely large structures.

## 1.4 Objectives of the Feasibility Study

The study was directed toward the accomplishment of the four objectives described below:

- The first objective was to determine the feasibility of placing fibers on a hull-shaped mandrel in such a way as to (1) cover the mandrel with fibers at a variety of angles, and (2) yield a structure conforming to the contours of the mandrel. The objective also called for positive findings to be verified by the production of a 1/48-scale filament wound hull.

- The second objective was to develop thickness specifications for filament wound hulls and to demonstrate the feasibility of winding structures of the specified thickness.

14

- The third objective was to determine whether the winding trials carried out during the study could be considered an accurate and complete demonstration of the feasibility of winding ship hulls of 200-foot length.

- The fourth objective was to formulate conclusions and make recommendations for a program that will lead to the production of full-scale ship hulls.

# SECTION 2

## FEASIBILITY OF PLACING FILAMENTS

## ON A HULL-SHAPED MANDREL

### 2.1  Hull Selection

The mandrels used during this part of the study were patterned
after the hull of a naval mine warfare ship (see Figure 6).
The use of such mandrels was dictated by the following consider-
ations:

- Mine warfare applications will be among the first to
  benefit from the availability of fiber-reinforced
  ship hulls;

- The multiple deck levels, negative curvatures, and
  irregular contours of mine warfare ships present a
  wide variety of obstacles to the winding process,
  all of which must be overcome in order to support a
  generalized conclusion as to the feasibility of fila-
  ment winding large ship hulls.

### 2.2  Hull Modification

Manual winding trials on a highly polished 1/200-scale model of
a mine warfare hull indicated that winding angles achievable at
the transition between deck levels (from deck level 01 to the
main decks aft) would be limited to those shown in Figure 7.
It may be practical to place enough fibers at these angles to
satisfy structural requirements while retaining the classical
stepped transition profile.  However, since a change in the

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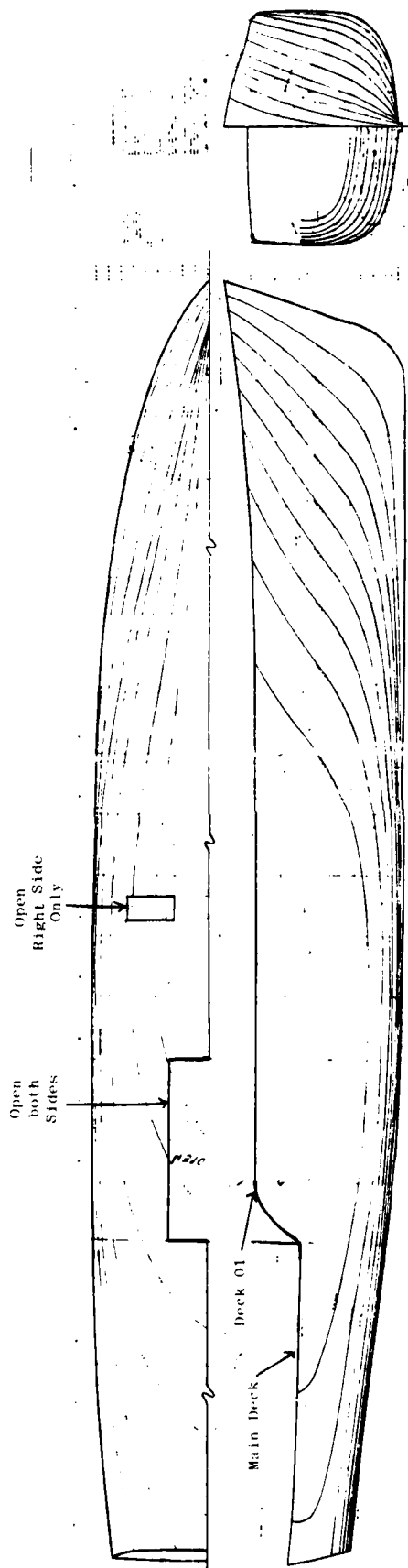
Figure 6.    Ship Molded Lines

Open
Right Side
Only

Open
both
Sides

Deck 01

Main Deck

17

DIRECT FILAMENT WINDING DOES NOT
COVER THIS AREA
(WILL REQUIRE PRE-MOLDED OR UN-
CURED RESIN-FIBER MATERIAL TO BE
WOUND IN)
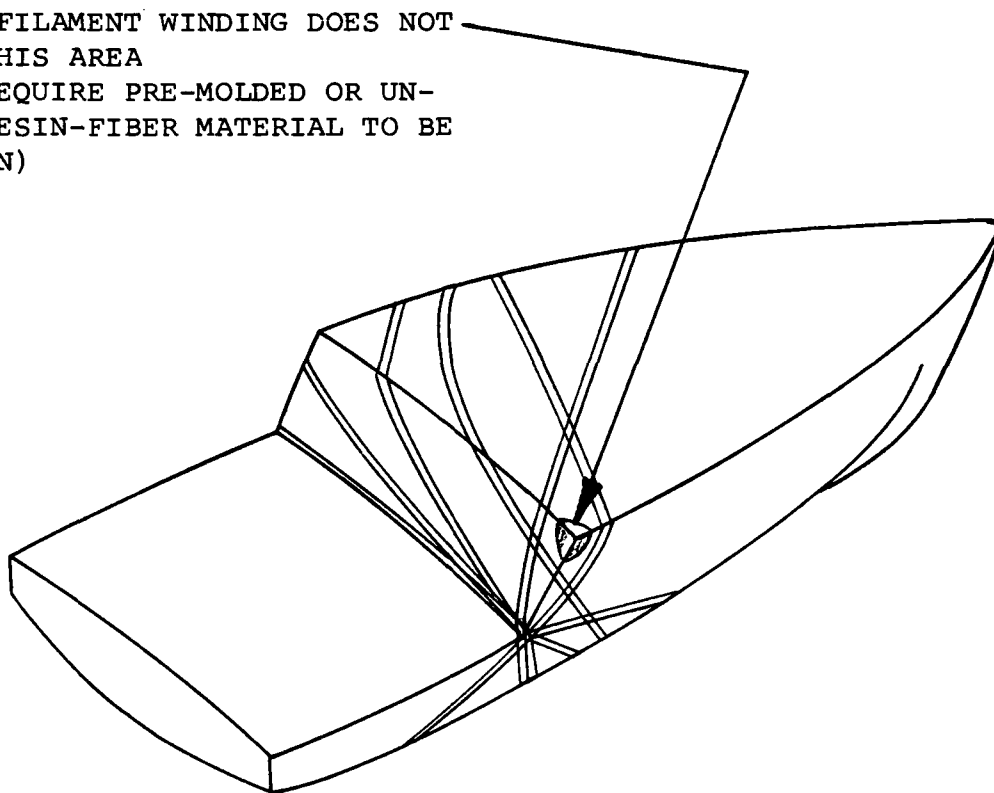
Figure 7.  Winding Angles at Transition
Between Deck Levels

18

transition profile was considered acceptable by the Navy's
Program Administrator, some time was spent with the 1/200-scale
hull in arriving at a profile that could be completely wound.

The best transition profile was determined to involve a section
of a 45-degree cone, with the large end of the cone toward deck
01 and the apex of the cone toward the main deck aft.    It was
also determined that the junction of the conical section with the
deck 01 aft should be changed to radii (see Figure 8).    This transi-
tion profile was incorporated into 1/48-scale mandrels for further
winding trials.
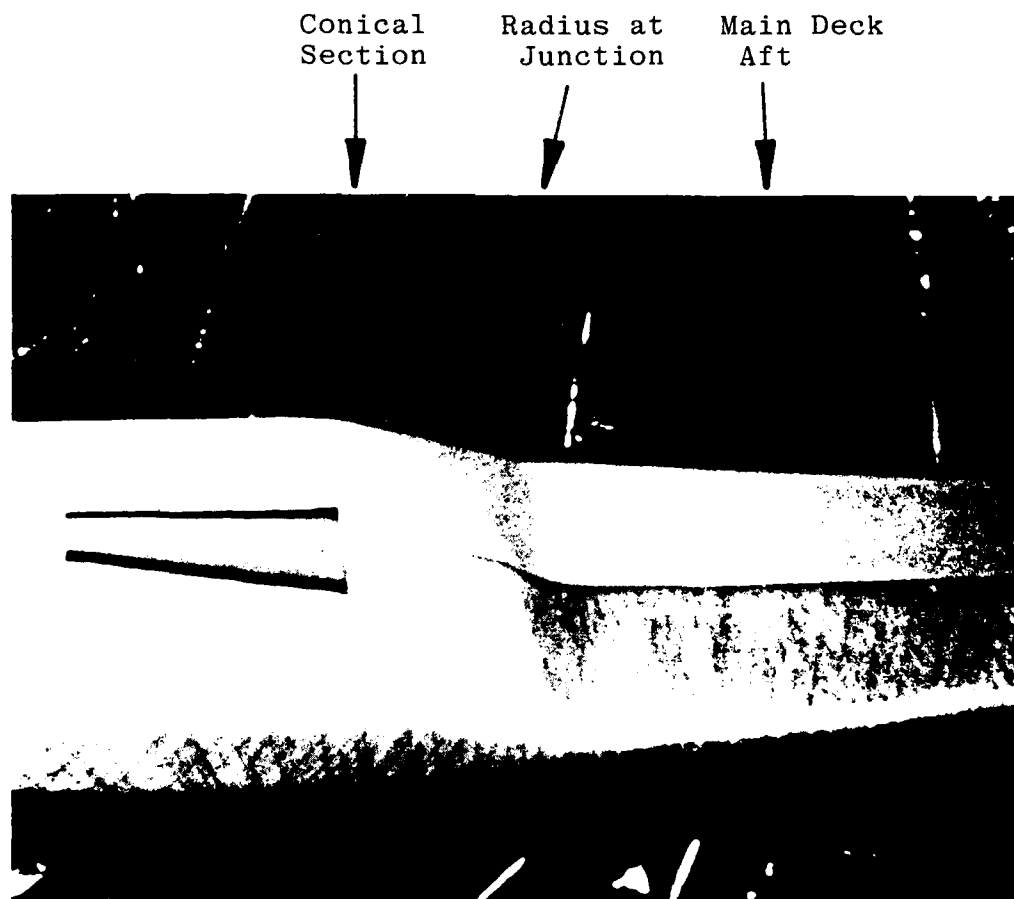


Figure 8.    Radius (Deck 01 to Main) at Junction of
             Conical Transition

## 2.3 Design of 1/48-Scale Mandrels

The mandrels used for winding trials on the McClean-Anderson Model W60 4-axis winding machine were 1/48-scale models of a mine warfare hull with a modified transition between deck 01 and the main decks aft. The junction of the hull walls with the decks was also modified to a smooth curve with a 1/4-inch wide radius, corresponding to a one-foot radius on a full size hull (see View A of Figure 9).

Initially, the mandrels were made by vacuum-forming 3/32-inch thick ABS plastic sheets on a wooden pattern. These mandrels were made as smooth and slippery as possible so that surface friction would not influence determinations of fiber path stability.

## 2.4 Selection of Mandrel Axis

The axis for mandrel rotation was determined by finding the center of the extreme dimensions of the mandrel cross-section at various points along the mandrel's length. The centerline formed by these points was used as a guide, with the axis being allowed to deviate from the line in order to exit below the main deck level at the stern. A one-inch diameter steel tube was extended through the mandrel on the modified centerline, and then chucked in the headstock and tailstock of the filament winding machine.

## 2.5 Selection of Filament Bandwidth

Ten 1800-yield rovings were formed into a 1/2-inch bandwidth for winding the 1/48-scale hull. This corresponds to the use of a

20

SECTION "A-A"

SECTION "C-C"

SECTION "B-B"
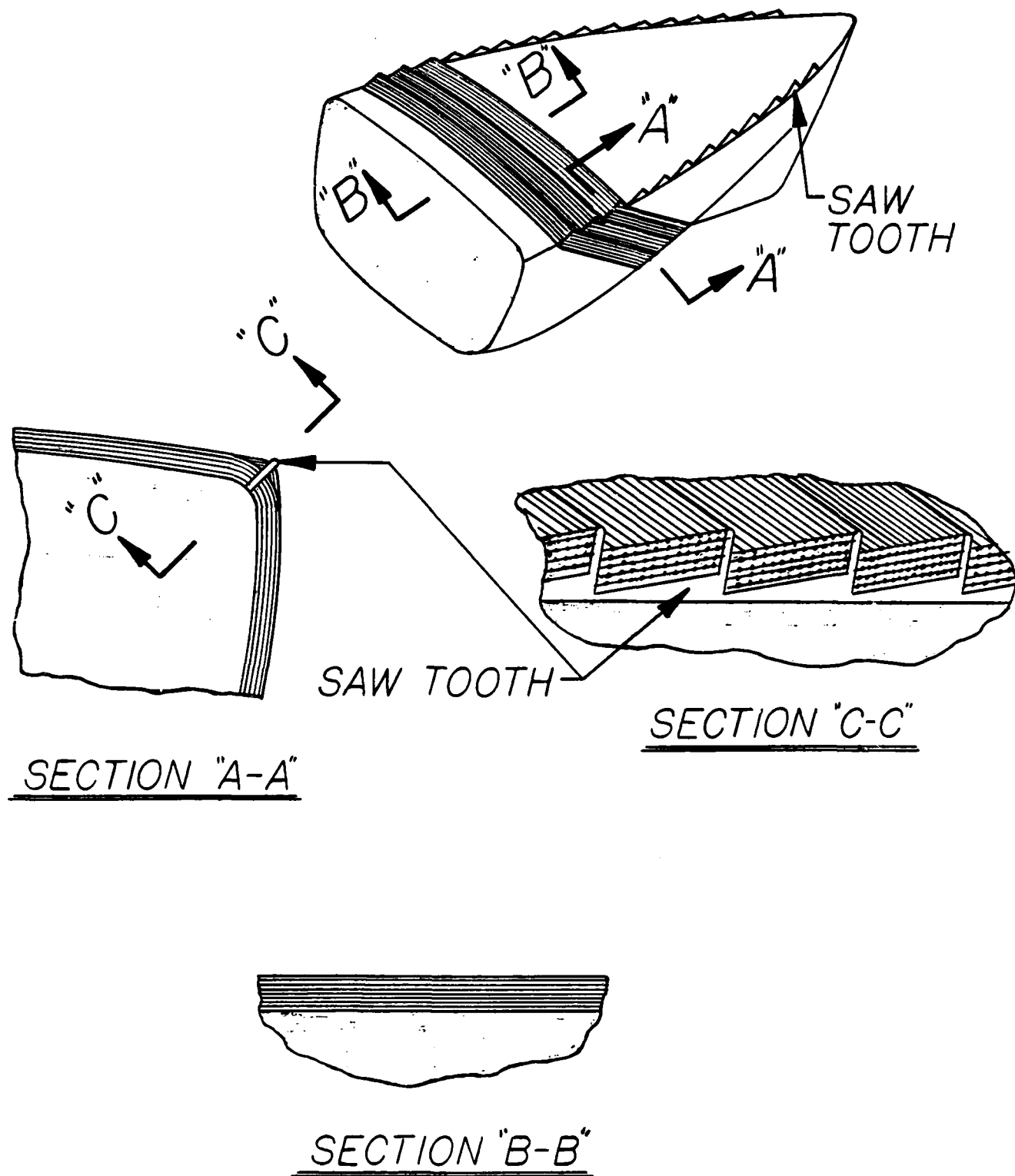
Figure 9. Radius at Junction of Hull Sides and Deck Surface

21

24-inch bandwidth for winding a full size hull.  Since 24-inch
bandwidths have been used successfully in industrial applications,
the 1/2-inch bandwidth was considered an accurate representation
of a feasible bandwidth.

## 2.6   Design of Filament Delivery System

The filament delivery system on a conventional McClean-Anderson
Model W60 4-axis winding machine achieves fiber placements with
variable horizontal movements of a carriage, crossfeed, and rotat-
ing delivery eye.   For the hull-shaped mandrel, however, a vertical
motion of the delivery system was determined to be necessary.   A
laboratory machine was, therefore, modified to include a vertical
motion capability.   The rotating eye capability was retained, but
instead of being controlled by computer, the eye was permitted to
rotate freely around the axis of the center of the fiber band.   The
elimination of rotating eye control had no effect, therefore, on the
determination of stable fiber paths.

## 2.7   Modification of Computer Software

The standard McClean-Anderson N-101 computer system on a W60 wind-
ing machine was modified to permit better control of the machine
during winding trials.   The modifications were as follows:

- The joystick controller that enables the operator to
  "fly" the W60 through a winding circuit was modified
  to provide improved response and more accurate control
  of the fiber delivery system.

- Capabilities for storage and playback of winding data
  were increased by incorporating a floppy disk drive
  into the N-101 control system.

22

## 2.8   Stable Fiber Paths

### 2.8.1   Stable Paths on a Hull with Modified Transition between Decks

The first winding trials (carried out with glass fibers and polyester resin on the W60 winding machine) utilized standard helical winding patterns generated by the N-101 computer.  From the stern to station 8 toward the bow (see Figure 6), the helical fiber paths appeared to be stable and generally satisfactory at winding angles between 70 and 85 degrees.  From station 7 to the bow, slippage occurred at these angles.

In an attempt to prevent fiber slippage near the bow, the W60 machine was operated manually with the joystick controller. Under manual control, fibers were placed on paths that started at high angles (70-85 degrees) at the stern, then changed to lower angles as the fibers approached the bow.  In many areas near the bow, non-slipping paths were determined to be very narrow, with areas of instability immediately adjacent on both sides.  At such locations, even slight deviation from the stable path resulted in fiber slippage.  In some cases, the stable path was less than 1/2 inch wide.  When that was the case, some of the fibers in the filament band remained in place, while others slipped.

### 2.8.2   Stable Paths on a Hull with Fiber Stabilizing Devices

When fiber paths are considered too unstable for satisfactory fiber placement, standard practice calls for the use of fiber stabilizing devices.  Since fiber paths near the bow of the mine warfare hull exhibited unsatisfactory levels of stability, special stabilizing devices were developed for the forward end

of the mandrel.   These devices were conceived as being similar

to "shelf" segments, arranged like fallen dominoes or sawteeth

at the bow stem and at the junction of the hull walls and the

forward deck (see Figures 9, 10, and 11).

Since shelf-type stabilizers would have to be positioned within

the contours of the ship hull in order for the wound hull to

retain its proper outer shape, their use would result in some

space being lost from the internal portion of the ship.   The

Navy's Program Administrator determined that such losses were of

no consequence for the purpose of this investigation, so further

winding trials were carried out on new, cast-foam mandrels equipped

with the shelf-type stabilizers.   Fairings would cover the shelves

of fibers to produce the desired hull contours.

The stabilizing devices performed as follows:   the angle of each

"shelf" was such that fibers approaching the device were at right

angles to the shelf.   As fibers approached and then passed over

the shelf, the band remained intact; the rectangular cross-section

of the band was preserved; and the fibers remained in place as the

winding proceeded.

> NOTE - The profile of full-sized stabilizers
>        could be curved slightly to exert a
>        flattening effect on the band, and
>        further detail could be introduced to
>        stabilize individual rovings or groups
>        of rovings passing over the shelves.
>
>        In addition, "dams" could be incorpor-
>        ated at the edge of the full-sized shelves
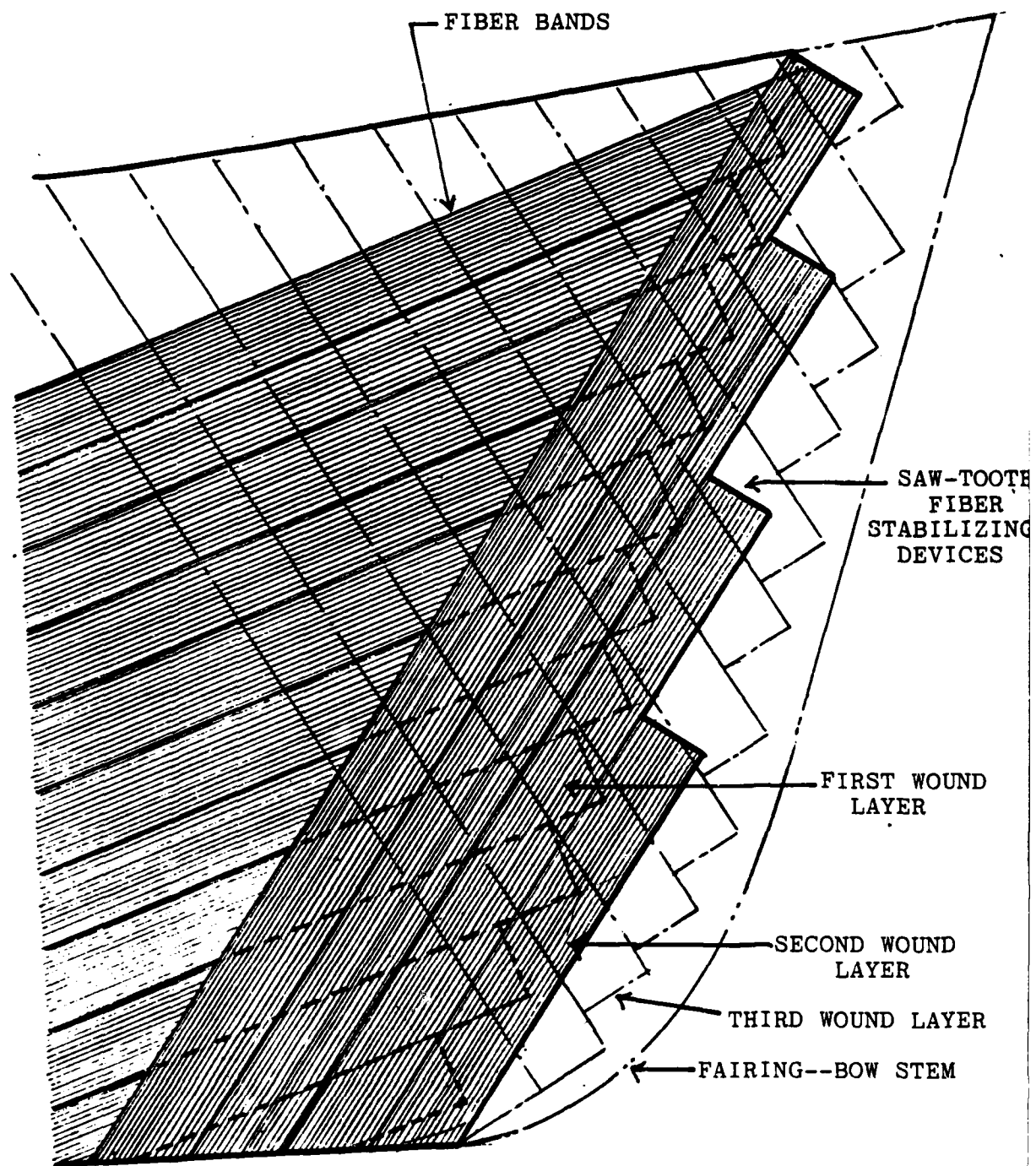
Figure 10. Saw-Tooth Shelves for
Band Stability (Bow)

25

Figure 11. Saw-Tooth Shelves for Band Stability (Deck to Hull Side)

to prevent fibers from spilling over
onto adjacent shelves. And in the course
of winding a full-size hull, new stabilizers
could be fastened to the mandrel as the
originals became covered with filaments or as
winding angles changed.

With stabilizers in place, winding angles of 70-85 degrees were
found to be feasible at all points on the mandrel surface. Mod-
erate angles of 45-60 degrees were then tried, with equal success.
Finally, winding angles in the 15-45 degree range were tried.
These angles, too, were found to be feasible at all points.

Throughout the winding trials, the machine movements required
for stable winding paths were automatically recorded
on floppy disks as a series of digital coordinates. The winding
paths differed in one respect from standard paths used for
conventional mandrels of uniform cross-section. This difference
can be summed up in the following manner:

In order to place fibers on a 33-degree path in the middle of a
uniform mandrel, a winding machine can begin a 33-degree winding
at either end of the mandrel and maintain the angle while winding
the entire length of the mandrel. During the course of cover-
ing the mandrel with 33-degree fibers, the target area will be
covered with fibers at this desired angle.

In order to achieve fiber placements at a 33-degree angle at a
given point on a hull-shaped mandrel, however, the winding
machine has to begin winding at a prescribed angle that may

27

differ from the 33-degree target angle. As the winding proceeds along a previously determined stable path, the winding angle will vary to maintain fiber stability despite variations in the contour and cross-sectional area of the hull shape. The targeted angle of 33 degrees will be achieved at the targeted spot only when a proper starting angle is selected.

For purposes of this study, it was not considered necessary to correlate specific starting points and starting angles with the achievement of specific winding angles at specific points on the mandrel surface. The winding angles achieved at various points were then summarized in tabular form (see Figure 12).

In the course of testing the full range of low, moderate, and high winding angles achievable on the hull-shaped mandrel, it was determined that the shaft extending from the bow of the mandrel presented an unnecessary obstacle to the achievement of accurate and stable filament placements. Since many industrial applications involve mandrels that are supported either in a canti-levered manner or in an intermittent manner with the use of a retractable support, it was decided to remove the shaft from the bow for further winding trials. (It would have been possible to wind the mandrel satisfactorily with the forward shaft in place, but removal of the shaft allowed the study to focus on issues directly related to feasibility.)

After the decision was made to remove the forward shaft, new mandrels were mounted on shafts extending solely from the stern (see Figure 13). It is acknowledged that a full size mandrel may need a retractable support on its forward end,

| | | Nom Angle | Bow 1/16 Pt | 1/4 Pt | Angle Mid Ship | 3/4 Aft | Stern |
|---|---|---|---|---|---|---|---|
| | | | **Stations** | | | | |
| Port Side | $\alpha$ | +45° | 40 to 60 | 45 | 45 | 45 | 45 |
| | $\theta$ | −45° | 40 to 60 | 45 | 45 | 45 | ±5 |
| Deck | $\alpha$ | +45° | 45 | 45 | 45 | 45 | ±5 |
| | $\theta$ | −45° | 45 | 45 | 45 | 45 | ±5 |
| Port Side | $\alpha$ | +67 | 70° | 67 | 67 | 67-75 | 67 |
| | $\theta$ | −67 | 75° | 67 | 67 | 67-75 | 67 |
| Deck | $\alpha$ | +67 | 70° | 67 | 67 | 67-90° | 67 |
| | $\theta$ | −67 | 70° | 67 | 67 | 67-90° | 67 |
| Port Side | $\alpha$ | +23 | 35 | 26 to 35 | 23 | 23 | 23 |
| | $\theta$ | −23 | 35 | 26 to 55 | 23 | 23 | 23 |
| Deck | $\alpha$ | +23 | 26 | 26 to 50 | 23 | *23 | 23 |
| | $\theta$ | −23 | 26 | 26 to 50 | 23 | *23 | 23 |

Note 1. Nominal angles are ±22½°, ±45°, ±67½°,   Midship
2. Bow and Forward Deck to sides require "sawtooth" devices--
see glossary.
3. *Requires pressure pads for deck 01 to main transition area.



Deck

$\alpha$ +Plus Wind Angle
$\theta$ -Wind Angle

1/16 pt  1/4 pt  Midship  3/4 aft  Stern

Port Side

Main deck

Transition deck 01 to main deck
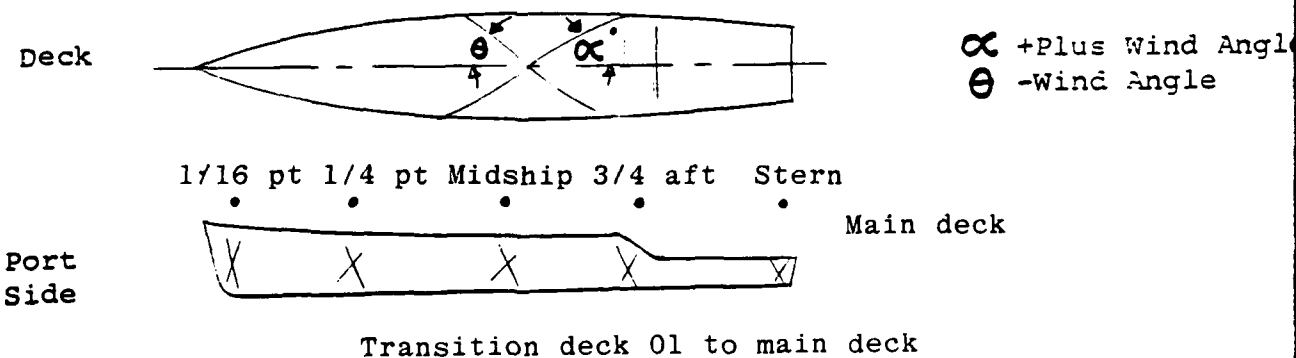
Figure 12. Winding Angles--from Bow to
Stern Port Side and Deck
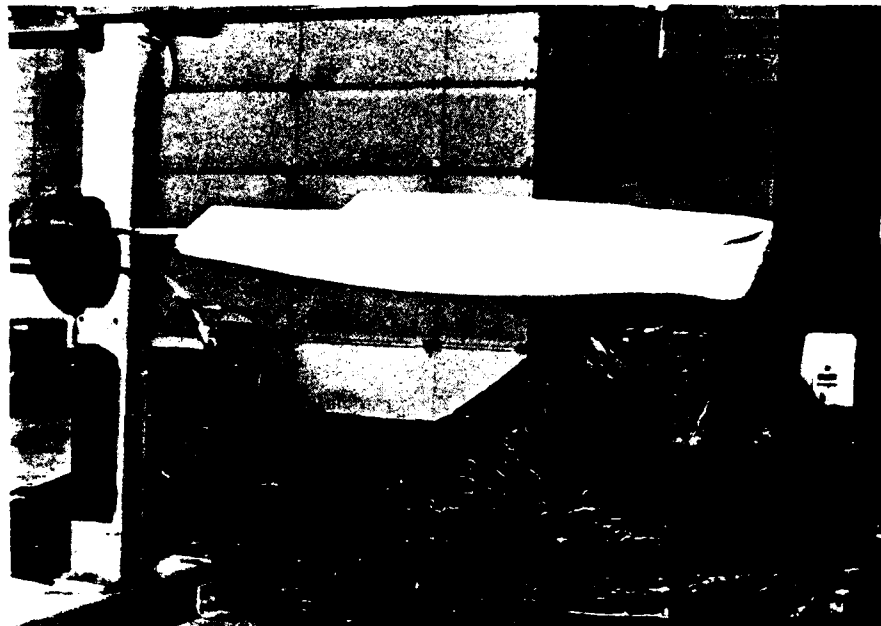
Figure 13.    1/48-Scale Model of Mandrel and Mounting

such as those used in a number of applications.*    When

fibers are to be placed in the area of support, the mechanism

would retract just long enough to allow the fibers to be

placed.    At all other times, the mechanism would remain in

position to help support the bow end.

## 2.9    Achieving Partial Coverage

In addition to identifying stable winding paths capable of

covering the entire surface of the hull-shaped mandrel at a

variety of winding angles, the winding trials on the W-60

winding machine identified paths suitable for covering limited

---

*    McClean-Anderson 16mm film shows such a device in action

portions of the mandrel surface. Such paths were considered of potential value for providing extra strength in localized areas.

At low angles, it was possible to cover parts of the bottom and sides of the hull without placing fibers on the deck (see Figures 14 and 15). It was also found possible to cover partial lengthwise sections of the hull--including the deck, hull walls, and the bottom of the hull--at a variety of angles without placing fibers on other hull sections. For instance, it was possible to wind the hull section situated between the deck transition area and the bow without winding the furthest aft section of the hull (see Figure 16).

## 2.10   Maintaining Negative Curvature

During the winding trials on the W60 filament winding machine, a number of stable fiber paths were found to exhibit "bridging" characteristics over the concave sections of the hull near the bow. T  areas where bridging occurred are shown in Figure 17.



REVERSAL POSSIBLE
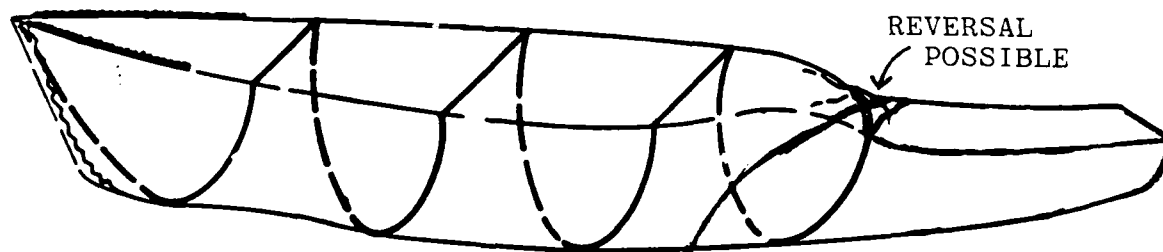
Figure 16.   Fiber Path Between Deck 01 to Main Deck
Transition Forward on Hull

31
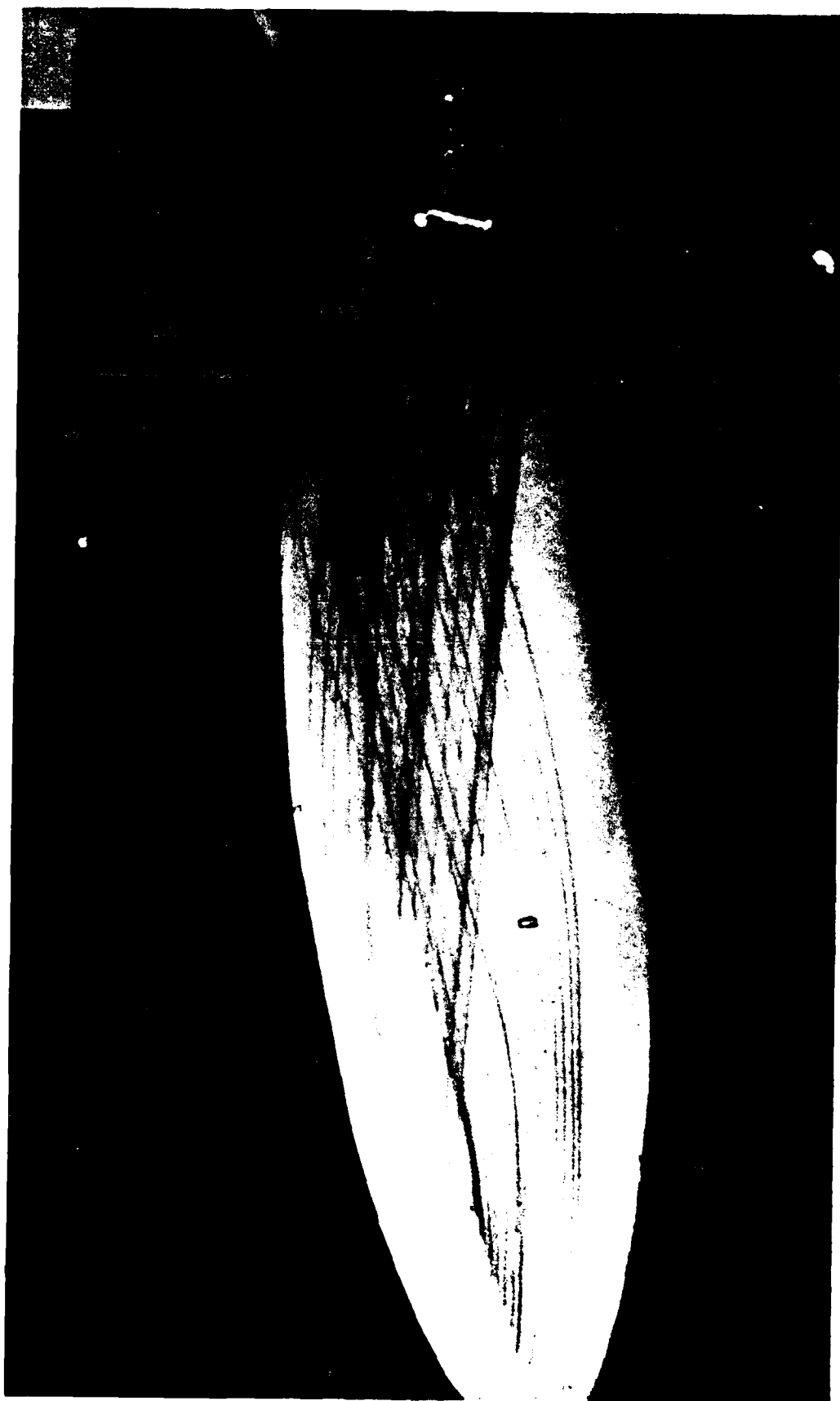
Figure 14.  Low Angle Winding--Bottom of Hull

FAIRING OVER WINDING
TO OBTAIN CONTOUR

FIBER BAND
INTEGRITY DETAIL          LOW ANGLES   15°-30°

MEDIUM ANGLES   30°-60°

HIGH ANGLES   60°-90°
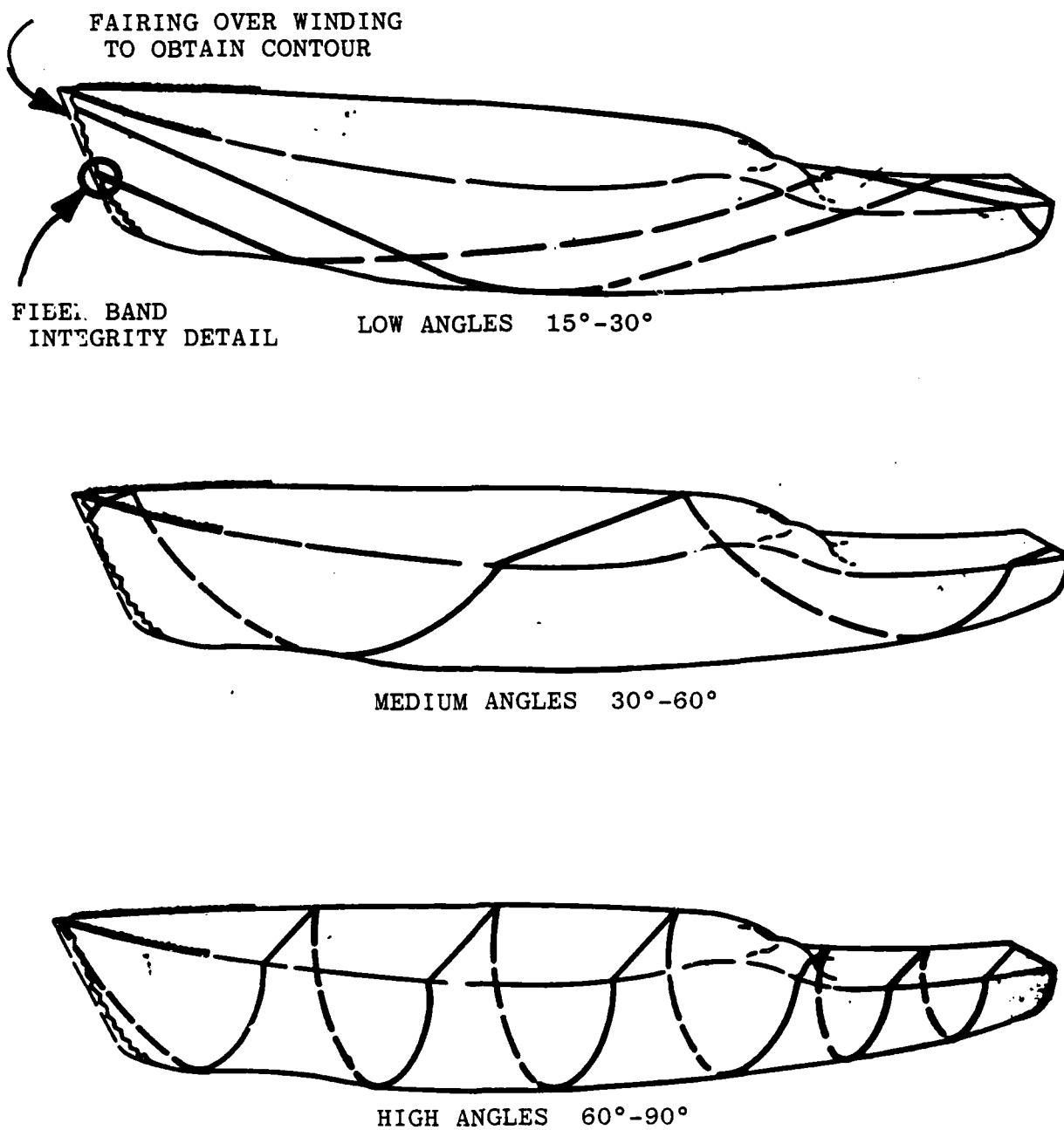
Figure 15.   Low Angle Winding--Bottom and Side of Hull

33
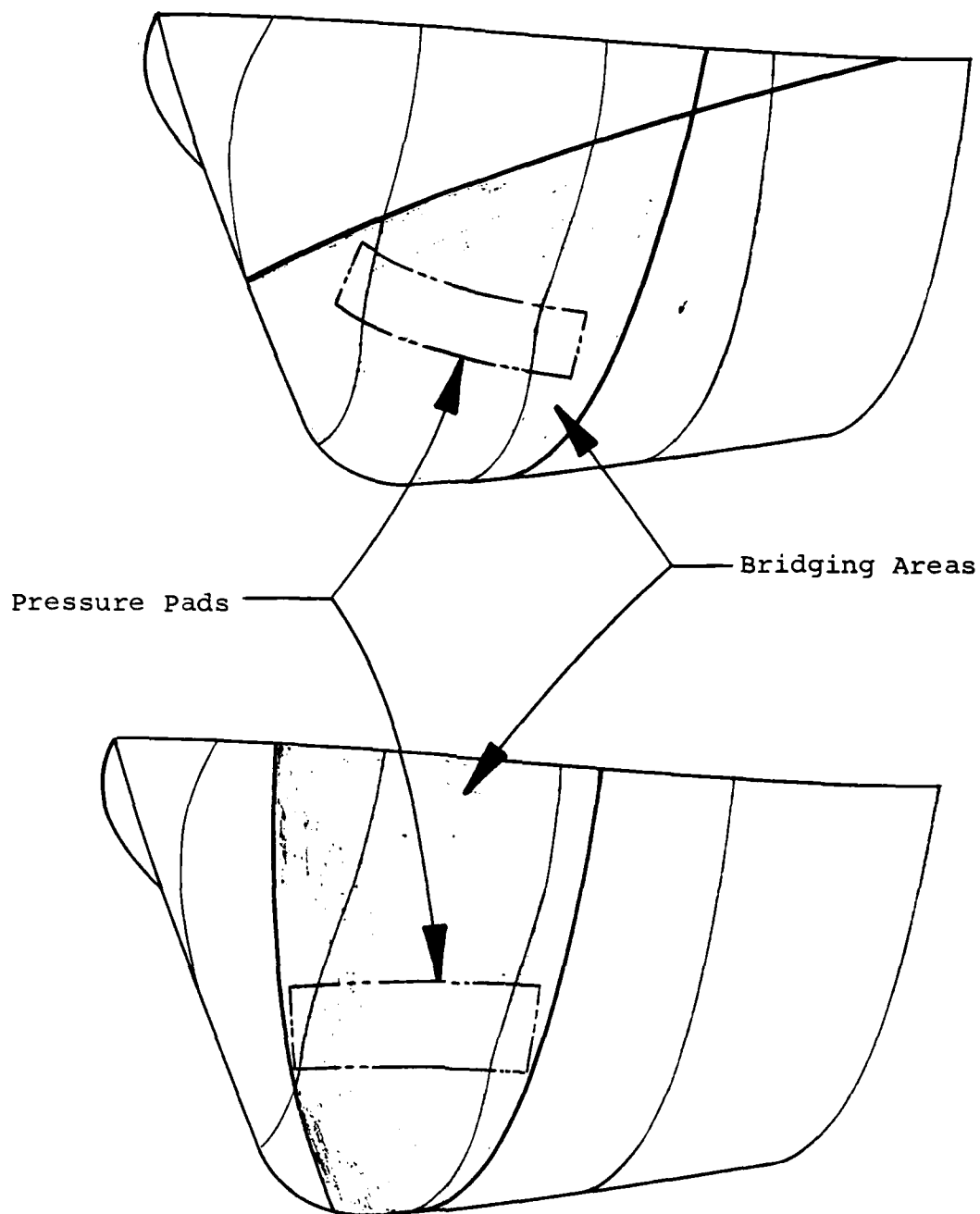
Figure 17. Paths and areas where fibers unaided do not contact hull surface.

A large scale mock-up of such sections was erected on a laboratory wall for analysis of the bridging forces and uncured fiber mass sagging estimate (Figure 18). Note: The Tension Scales on the ends of the rovings (Figure 18A) were used to simulate the strain (stretch) of rovings during full-scale hull winding. This effective stretchable length will be 300 to 500 feet at 9 lbs tension per roving; for example, the stretch will be approximately 3 inches for 225-yield roving.
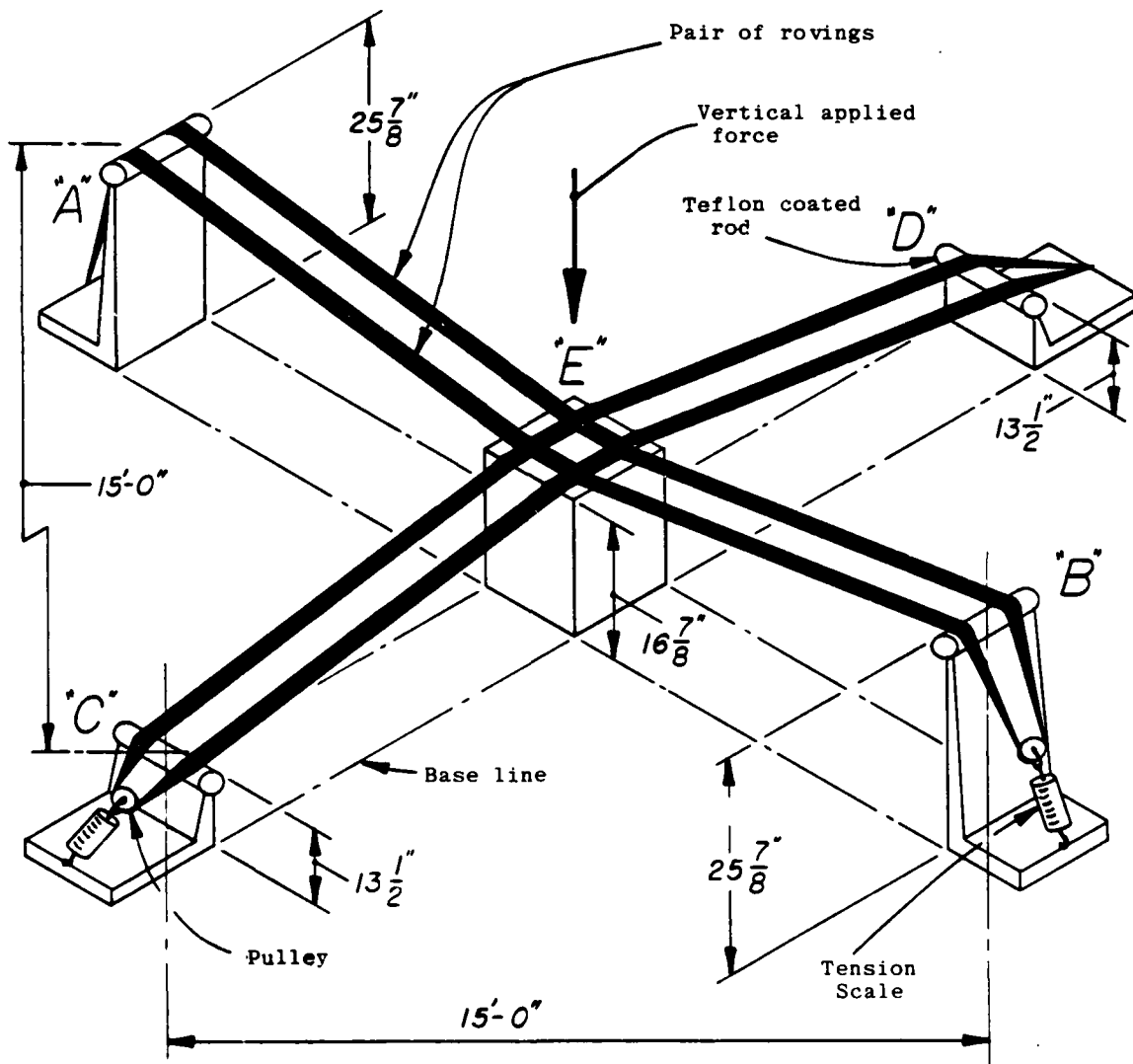


Figure 18A.   Pad Forces Applied at E to Deflect Fibers to
              Contact Concave Surface (see data on Fib. 18B).

35

PAD FORCES APPLIED AT E (Fig. 18A) TO DEFLECT FIBERS

| WITH A CONSTANT TENSION ON A PAIR OF ROVINGS BETWEEN A & B OF | THE FORCES REQUIRED TO DEFLECT ROVINGS BETWEEN C & D, FOR THE DEFLECTIONS SHOWN WERE | | | THE FORCE AT E REQUIRED TO DEFLECT THE PAIR OF ROVINGS 9 INCHES WAS | THE FORCE AT E REQUIRED TO LIFT THE FIBERS BETWEEN A & B WAS | THE FORCE AT E REQUIRED TO LIFT THE FIBERS BETWEEN C & D WAS |
|---|---|---|---|---|---|---|
| | Deflection | | | | | |
| | 4½" | 6 3/4" | 9" | | | |
| 10-13 lbs | 9 lbs | 24 lbs | 63 lbs | 1.75 lbs | 5 lbs | 10 lbs |
| 8 - 11 lbs | 7 lbs | 22 lbs | 53 lbs | 1.6 lbs | 5 lbs | 8 lbs |
| 6 - 7 lbs | 5 lbs | 18 lbs | 46 lbs | 1.4 lbs | 4.5 lbs | 6 lbs |
| 4 - 5.5 lbs | 3 lbs | 11 lbs | 34 lbs | 1.0 lb | 3.5 lbs | 4 lbs |
| 2 - 3 lbs | 1 lb | 6 lbs | 20 lbs | 0.6 lb | 2 lbs | 2 lbs |

Figure 18B.  Lifting (Sagging) Forces for Various Fiber Tensions (see Figure 18A)

The analysis determined that the force required to hold the
bridging fibers against the negative curvature was greater
than the force that could be generated by applying non-bridging
fibers on top of the bridging fibers.  As a result, it was con-
cluded that pressure pads would be required for holding fibers
against the concave sections during the winding and curing pro-
cess.  It was further concluded that the forces required for
maintaining the negative curvature were well within the operating
capability of pressure pads currently in use (see Figure 19A).
It was also concluded that uncured fiber/resin in thick sections
would sag; that is, pull away from the flatter sections of the
winding mandrel.  To overcome this condition the uncured fiber/
resin portion could only be thick enough so that its weight would
be less than the adhesive forces and, therefore, would not pull
away from the previously deposited fiber structure (see Figure 19B).

2.11  Filament Winding of 1/48-Scale Hulls

When the winding trials were finished, two complete 1/48-scale
hulls were produced on the modified W-60 filament winding machine
to demonstrate the feasibility of placing fibers at a variety of
angles on all parts of the hull surface.  In order to produce
wall thicknesses in scale with the mandrel size, only three
major winding angles could be used.  Therefore, a combination
of low, moderate, and high angles was selected to represent
the feasible angles identified during the winding trials.

During production of the 1/48-scale hulls, no attempt was made
to place fibers on the hull stern.  Instead, an assumption was
made, with concurrence of the Navy's Program Administrator,

37

BRIDGING

PAD FORCE REQUIRED
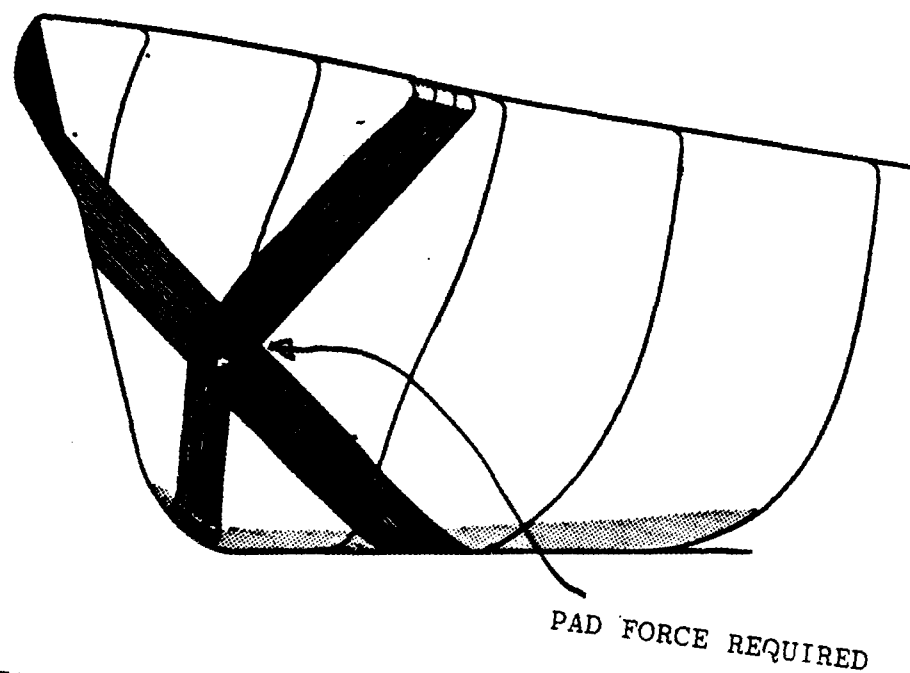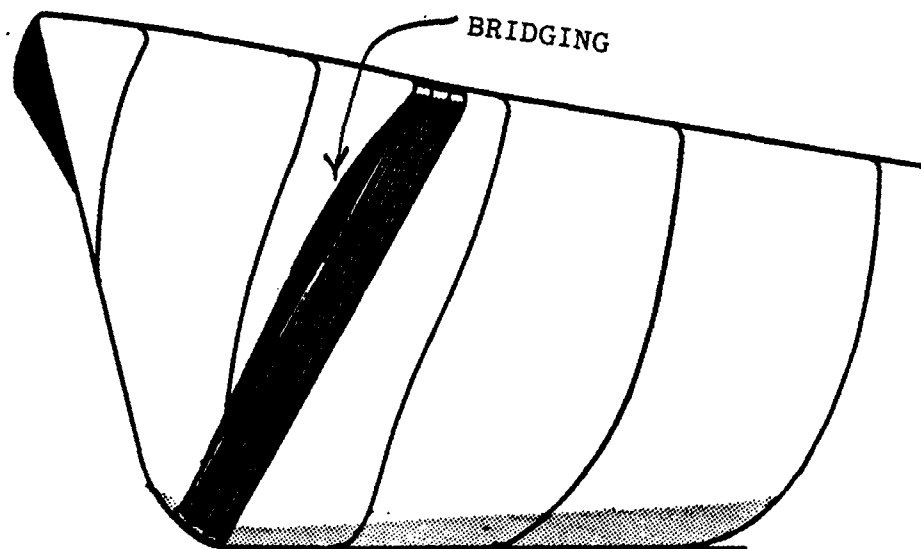
Figure 19A. Need for Pads to Maintain Fiber
Bands on Concave Surface

38

HULL MANDREL

GAP DUE TO WEIGHT OF
WALL OF UNCURED FIBER/
RESIN EXCEEDING WHEN
ADHESIVE ABILITY OF
RESIN IS EXCEEDED

SAG IN FILAMENT
WOUND STRUCTURE
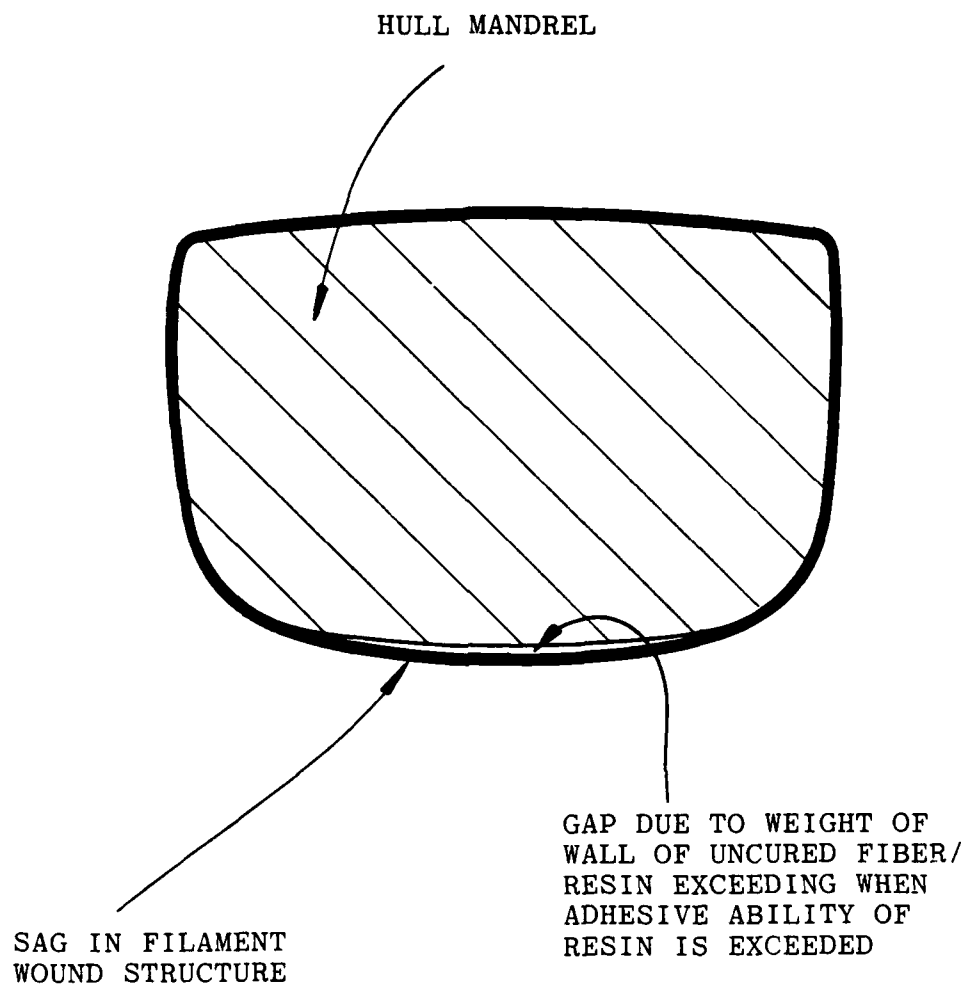
Figure 19B.    Uncured Thick Laminate Mandrel
               Interface

39

that the stern could be fabricated separately and attached to the hull afterward. The opening at the aft end of the wound structure was used for removal of the cast foam mandrel after the winding was completed. The total winding time for fabrication of each hull was approximately four hours. The finished hull walls contained six layers of fibers, with a total thickness of approximately 0.060 inch.

Pads cast to match the concave sections of the hull were used to force bridging fibers into contact with the mandrel surface. The pads were covered with a non-sticking film and clamped into place after the hull was wound. They were left in place until the winding was cured. (For full size windings, the clamps would be applied intermittently during the winding, being removed only long enough to permit new fibers to be placed in the area.) The first hull to be wound was dissected for analysis of wall thickness. The second hull was left intact, and large hatch openings were cut into it for demonstration purposes (see Figure 2). No attempt was made during the winding to reinforce the area surrounding the planned hatch opening, but design concepts for such reinforcements have been developed previously.

2.12 Form Draping a 1/48-Scale Hull

A sheet of fiber material measuring 26 inches by 75 inches by 0.060-inch thick was created by winding six layers of 1800-yield glass rovings and polyester resin on a 26-inch section of a cylindrical mandrel measuring two feet in diameter. Winding angles of ±45 degrees, ±80 degrees, and 0 degrees were used (Fig. 20A). After the fiber material was wound, it was cut from the mandrel

40

±80° Windings

±45° Windings

0° Windings

Rotation

One cut to allow
removal

Sequence of Layers

±45° - one layer each
±80° - one layer each
0°    - one layer
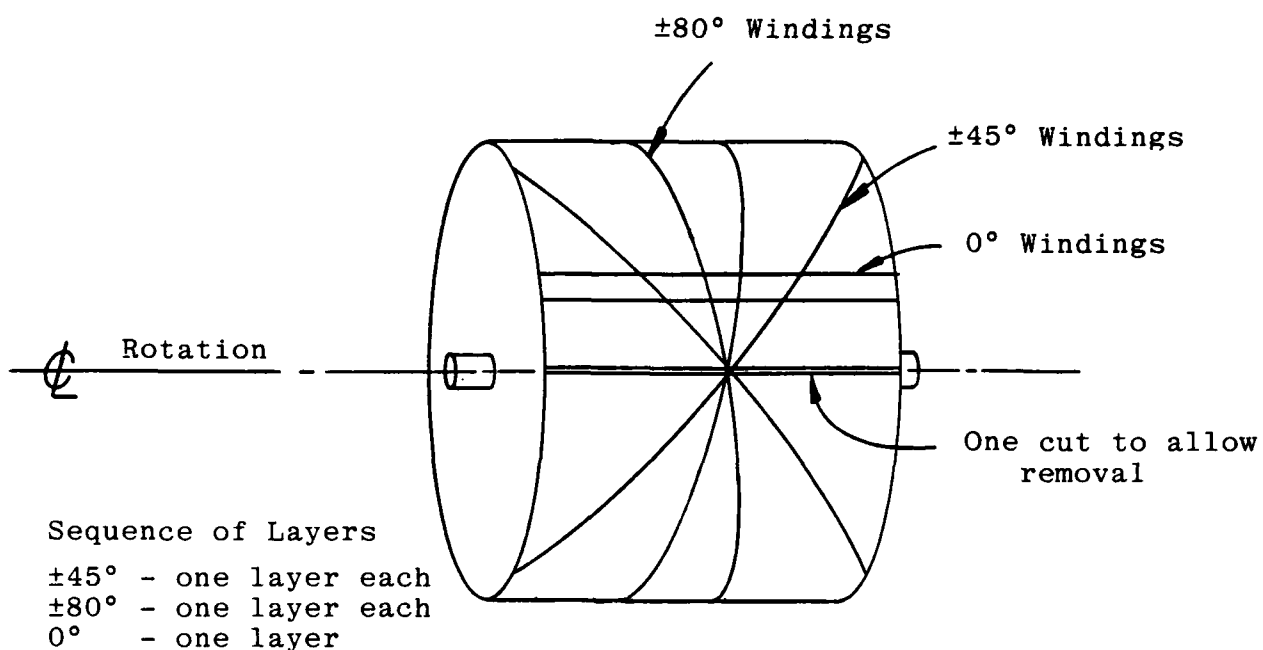
Figure 20A.    Filament Winding on 12-inch Diameter Mandrel

90° layer

±45° Layers

±10° Layers
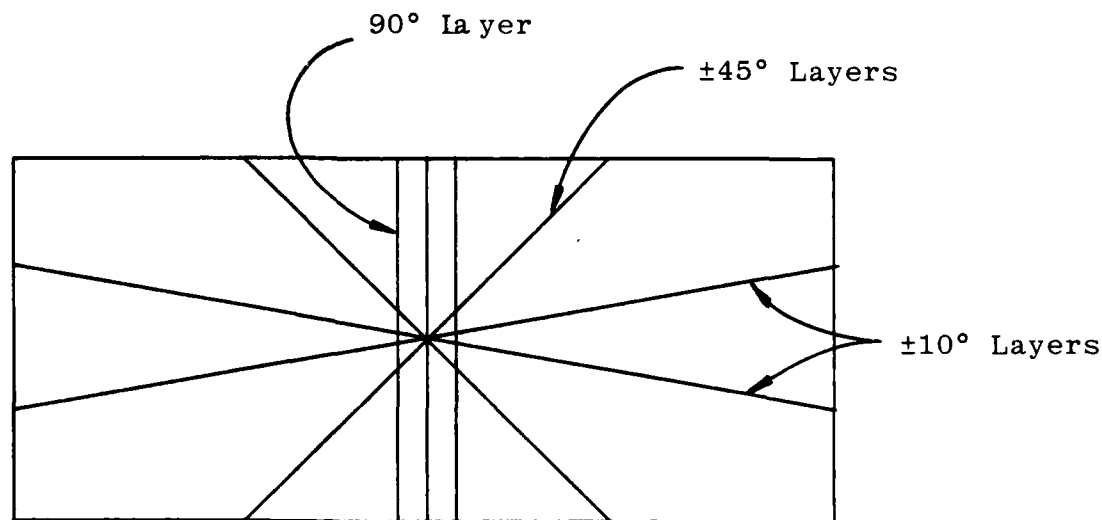
Figure 20B.    Flat Filament Wound Sheet for Draping
Obtained from Winding Above

41

and draped onto a 1/48-scale hull-shaped form situated below the mandrel. The angle relative to the longitudinal axis of the hull then became ±45 degrees, ±10 degrees, and 90 degrees (see Figure 20B). In most areas, the material rapidly conformed to the profile of the hull. In the area of negative curvature, the material was "patted" against the form and then remained in place. In places where the material was distorted by air bubbles or wrinkles, gentle hand pressure was sufficient to smooth out the distortions (see Figure 21).



Figure 21.    Smoothing Distortions in Fiber Material

The weight of the excess material draped over the bow caused the fiber material in that area to efface, or become thinner. No holes were created by the effacement.    Distortion of fiber paths in the material was revealed by colored tracer threads. The lines of distortion are shown in Figure 22.

42

**±45°**  **+25°**
**−70°**

Distortion
Nom. ±45°  **+65°**
**−40°**

**±45°**

Port Side

**±45°**  **±45°**  **+50°**
**−55°**

Bottom View

NOM. ±45°   FIBER ORIENTATIONS

Nom. ±10°  **+5°**
**−15°**  **±7°**  **+25°**
**−4°**

Port Side

Actual angles  **±13°**

Nom. ±10°  **±11°**

Bottom View

NOM. ±10°   FIBER ORIENTATIONS

Actual Angles

**±70°**  **90°**  **90°**

Nom. 90°  **90°**

Port Side

NOM. 90°   FIBER ORIENTATIONS
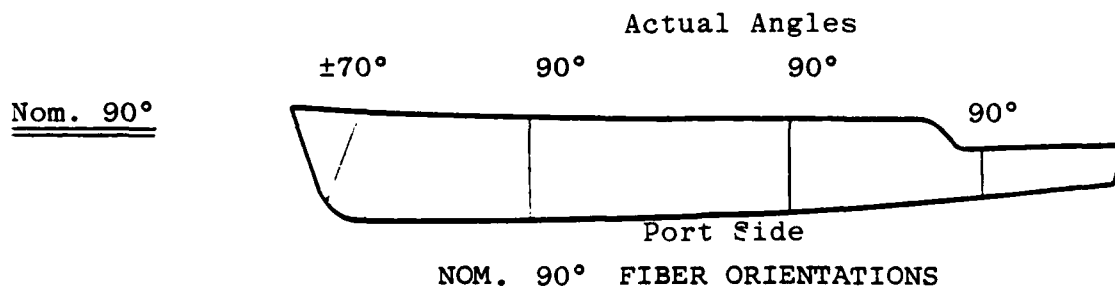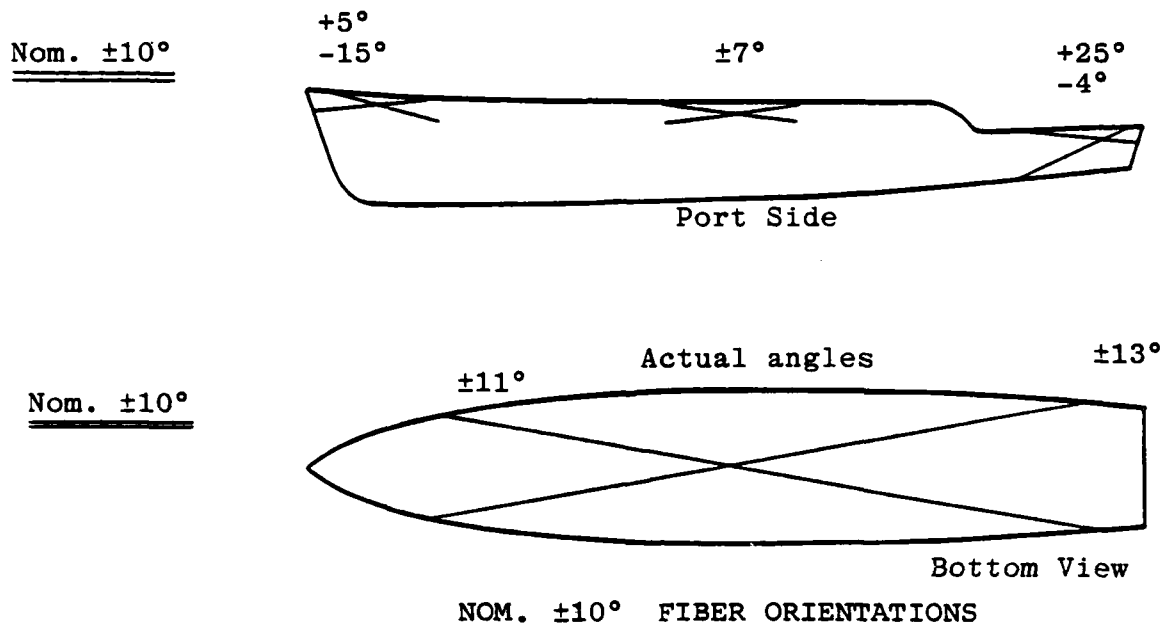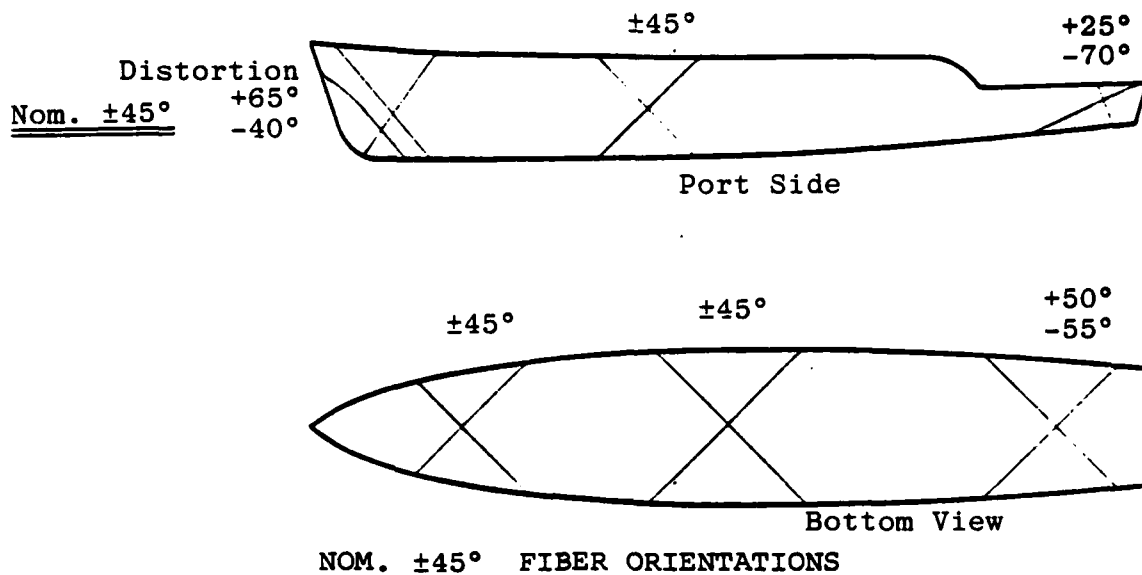
Figure **22.**   Fiber Orientations at Various Locations

43

Excess fabric was trimmed from the form, leaving one inch of material for draping onto the deck of the form. After the edges of the material were fastened to the deck, the draped hull was heat cured.

No other draping trials were conducted, because direct placement of fibers on hull shapes had been proven feasible during the machine winding trials.

Questions requiring further study before the form draping process can be considered feasible for producing large ship hulls include the following:

- Can large sheets of filament wound material be successfully transferred from a mandrel to a full size hull form, or will it be necessary to use a number of smaller sheets to drape a single large form?

- How can large sheets of material be retained in place on the form during the curing process?

- What kind of apparatus will be needed for smoothing out distorted areas and "patting" large pieces of fabric against areas of negative curvature?

- Will the fiber/resin laminate require outside pressure over a large portion of its surface in order to prevent sagging away from the mandrel?

- At what rate or rates should the material be cured after it is placed on the hull form?

44

# SECTION 3

## FEASIBILITY OF PRODUCING STRUCTURES OF THE THICKNESS
## REQUIRED FOR A SHIP HULL 200 FEET LONG

### 3.1    Determination of Required Thickness

Merlin Technologies, Inc., San Jose, California, developed wall
thickness specifications for full-size windings of marine warfare
hulls.  The specifications incorporated a safety factor of 2.0
for hull and deck loads of 500 lbs per square foot and 250 lbs
per square foot, respectively.  The thickness specifications
assumed the use of quasi-isotropic windings with 50 percent of
the fibers oriented at ±45 degrees, 25 percent of the fibers at
0 degrees, and 25 percent of the fibers at 90 degrees.

### 3.1.1  Analysis of Thickness Requirements

Graphite/epoxy and fiberglass/epoxy windings were evaluated.
Fiberglass/epoxy windings were determined to be less costly, though
somewhat heavier than graphite/epoxy windings for the hull wind-
ing application.  A fiber volume of 60 percent was used in
determining the material properties and strengths shown in
Table A-1 in the Appendix.  The effects of adding frames to
the structure were investigated in this study.  All of the
frames are assumed to be fiberglass.

Depending upon the hull's frame spacing, the required thickness
of fiberglass/epoxy walls was determined to be between 0.121
and 4.826 inches.  The hull and deck were analyzed as a series

45

of flat panels under normal, uniformly distributed load of the magnitudes mentioned above. Complete displacement and rotational restraint is assumed along the four edges of each panel. The results of this work are summarized in Figure A-1 through A-4 in the Appendix. The first of these figures plots the hull laminate thickness required to limit deflections as a function of frame spacing for both materials. The limit on deflection is about 1.86 times the laminate thickness, which is the limitation of small-deflection theory considering membrane behavior. For a given frame spacing, the required E-glass thickness is considerably larger than the required HS graphite thickness, reflecting the lower modulus of the glass laminate. The calculations were based upon graphite fiber of modulus E of 33 million.

Figure A-2 illustrates the relationship between maximum hull panel deflection and frame spacing for the two materials. Deflections become very large for frame spacings greater than about 140 inches for graphite, and about 100 inches for E-glass.

Figure A-3 plots deck thickness and frame spacing. Thickness is smaller than the required hull thickness at any frame spacing because the imposed loads are smaller for the deck than for the hull.

Figure A-4 presents maximum deck deflection as a function of frame spacing. Deflections become quite large for frame spacings in excess of about 130 inches for E-glass and 160 inches for graphite.

Optimum frame spacing is determined from a weight standpoint. However, frames represent additional manufacturing and installation costs which are not considered here, so the determined

46

optimum spacing may change once these costs are determined. Also, it has been tacitly assumed that winding cost is the same for graphite or glass fiber.

The optimum frame spacings, from a total weight standpoint, are approximately 30 inches for E-glass skin and 40 inches for graphite skin. At these spacings, fifteen and eleven intermediate frames are required over a bay of 480 inches. The hull and deck segment weights, as well as intermediate frame weights for HS graphite and E-glass laminates, are summarized in Table 1 below.

| Skin Material | Weight of Deck Segment (lbs) | Weight of Hull Segment (lbs) | Weight of Frames (lbs) |
|---|---|---|---|
| E-glass | 4,091 | 14,600 | 40,080 |
| Graphite | 3,392 | 12,100 | 36,000 |

Table 1.  Hull and Deck Weights

Since the estimated cost of E-glass/epoxy material is $1.00/lb, and that of graphite/epoxy is $12.00/lb, E-glass is clearly the more cost effective material. Optimizing frame spacing with respect to material cost indicates that a very close spacing (such as 12 inches) produces the least expensive material requirements. The material requirements for a graphite ship would be about 4,500 pounds of graphite/epoxy and 63,000 pounds of glass/epoxy for intermediate frames. At the prices quoted above, material costs for the graphite structure would far exceed those of the E-glass structure.  In addition, the

47

very large number of frames would introduce much higher manufacturing and assembly costs.  In summary, graphite/epoxy would become attractive only if weight or stiffness considerations became more important than cost.

Figure A-5 presents a plot of total structure weight versus frame spacing for E-glass material.  The fact that the curve is very flat between frame spacings of 20 to 60 inches indicates that manufacturing and assembly costs will play a role in determining the final frame spacing.  The steepness of the curve beyond a frame spacing of 120 inches indicates that this spacing should be regarded as a practical maximum value, unless a structure essentially without frames is desirable.  The hull structural weight with frame spacing of 25 feet, a hull deck of 1-1/2 inch thickness, and a hull thickness of 3-inch fiberglass is calculated to be 50,000 lbs for a 40 foot by 40 foot section.  This is approximately three times the minimum weight obtained with 2 foot frame spacing.

3.1.2    Thickness Study Conclusions and Recommendations

The conslusions of this study can be summarized very briefly:

(1)    The filament wound concept is structurally feasible.
(2)    E-glass is clearly the more cost-effective material for both the hull and deck.
(3)    Optimum spacing for intermediate frames is 30 inches for minimum weight.

Areas which require further effort are:

(1)    Further definition of applied loads.
(2)    More detailed analysis of local areas is required.

The first recommendation derives from the fact that the 500 lb per square foot and 250 lb per square foot loadings are understood to be envelope values.  If the actual applied loads can be defined more precisely, frame spacing and skin thickness can be varied to further optimize the deck and hull structure.

48

Once fiber orientations are finalized, the second recommendation can be implemented to determine the amounts of local reinforcement required in areas such as the step to the aft deck.

## 3.2    Production of Hull Sections of the Required Thickness

A six-foot long mandrel having one flat side and one curved side having a 12-inch radius was used for this part of the study so that the results would apply to the full range of surface curvatures found on a mine warfare hull.    See Figure 23.

Twelve 225-yield glass rovings were paired to simulate size 113-yield rovings, then formed into a 3/4-inch bandwidth and wound at ±30 degrees for the first four layers of the winding. Some 62 additional layers of fibers were placed on the mandrel at angles of ±45 degrees and at 90 degrees to create a structure approximately three inches thick.    The total winding time was approximately nine hours.

A progressively curing dual resin system was employed to reduce shrinkage while maintaining a primary bond between layers of the winding and separate resin coated fibers which were brought together when the band was formed.    It was also used to demonstrate a method for eliminating the sagging of thick heavy fiber/resin in large ship hulls.

The curing rate was controlled to assure the following relationships between succeeding layers of the winding (see Figure 24):

- As resin-impregnated fibers were wound onto the mandrel, they were placed on top of previously applied fibers whose resin was still in the A-stage.
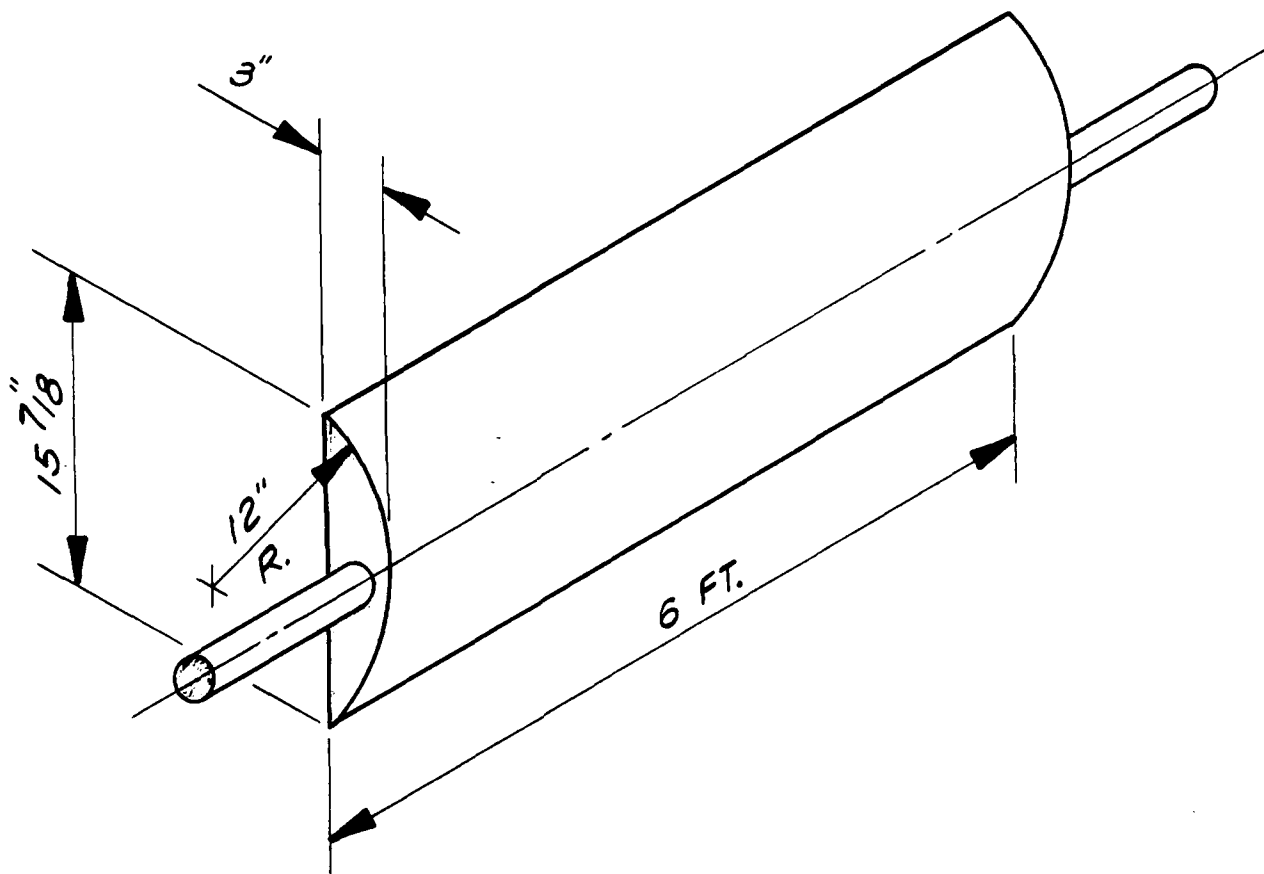
Figure 23.    Mandrel for Winding Thick Sections
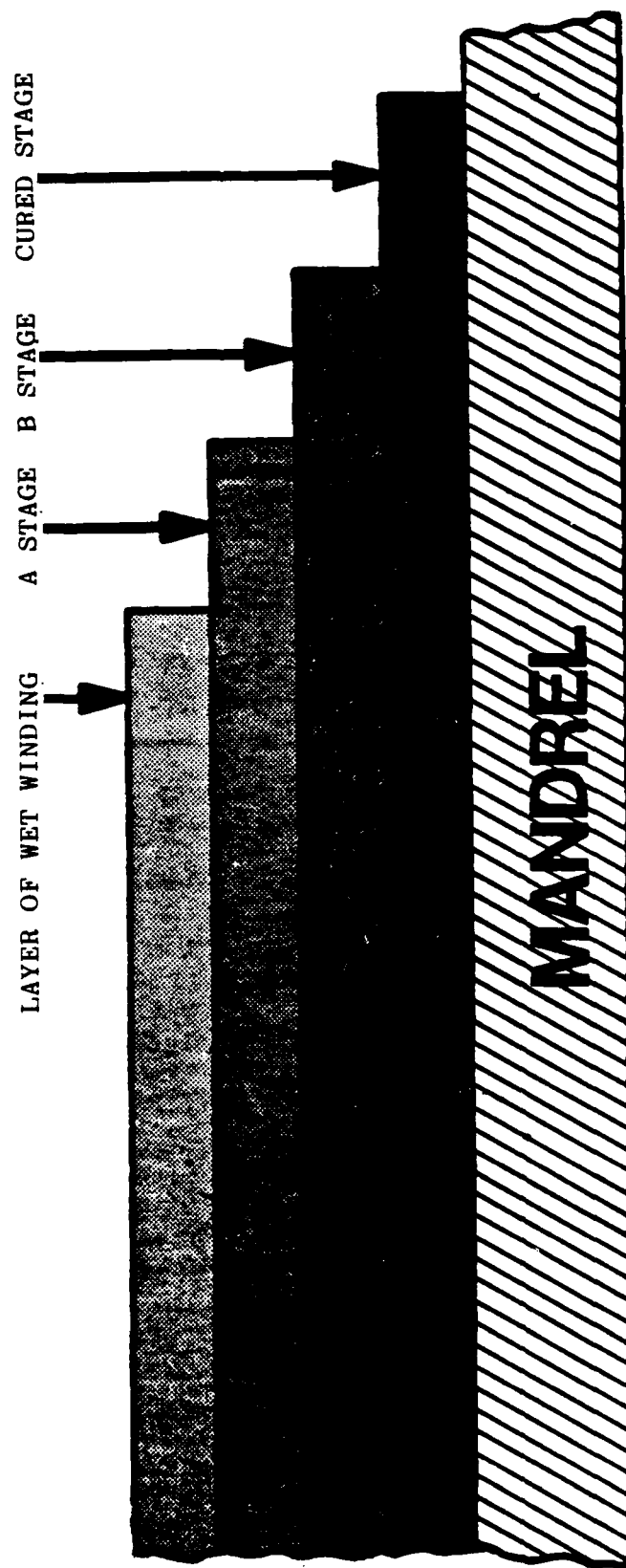
Figure 24. Controlled Cure During Winding

51

- Beneath two layers of the A-stage fibers, resin adhering to previously placed fibers was in the B-stage (during which half of the resin shrinkage occurs).

- Beneath the B-stage fibers, the resin adhering to fibers placed still earlier was in the C-stage (by which time the resin has essentially finished shrinking, and has achieved 90 percent of its final strength).

Both the flat and curved sections of the cured winding were examined for failure cracks, but no such cracks were found. The entire winding was determined to have withstood the reduced shrinkage associated with the in-process curing without showing cracks or other interlaminar failures.

## SECTION 4
## FEATURE DESIGN

### 4.1 Deck Openings

The technique shown in Figure 25 can be used to make either small
or large hatches. It has been used successfully on highly stressed
missile type structures, where openings are made in the walls.

At hull positions where hatch openings are required, wafers are in-
serted between layers during winding of the hull. The wafers con-
sist of circumferentially wound fibers of one to perhaps five fibers
in thickness. They can be made by circumferential winding between
two plates. The wafers are left in the uncured stage and flared be-
tween winding layers. After cure, the fibers crossing the openings
can be cut and the edges shaped to match the hatch requirements.
Softening rings of glass mat or dynel felt can also be inserted to
allow the edge of the openings to strain more than the adjacent
structure with little increase in stress.

The technique shown in Figure 26 can be used for small openings. It
has been used to make holes in wound structures to eliminate hole
layout, drill jigs, and the need for drilling through wound structures
after cure.

A method successfully used for inserts is shown in Figure 27.
An insert, plastic or metal, is placed in position on the
mandrel. A shaped plug is used, as shown, to deflect the fibers
around the insert. With larger holes, there may be a need for
circular patches of wound or cloth material between layers.

53

HATCH OPENING FIBERS
CUT AWAY AFTER CURE

WINDING
PATTERNS

SOFTENING RING &
WAFER INSERTS
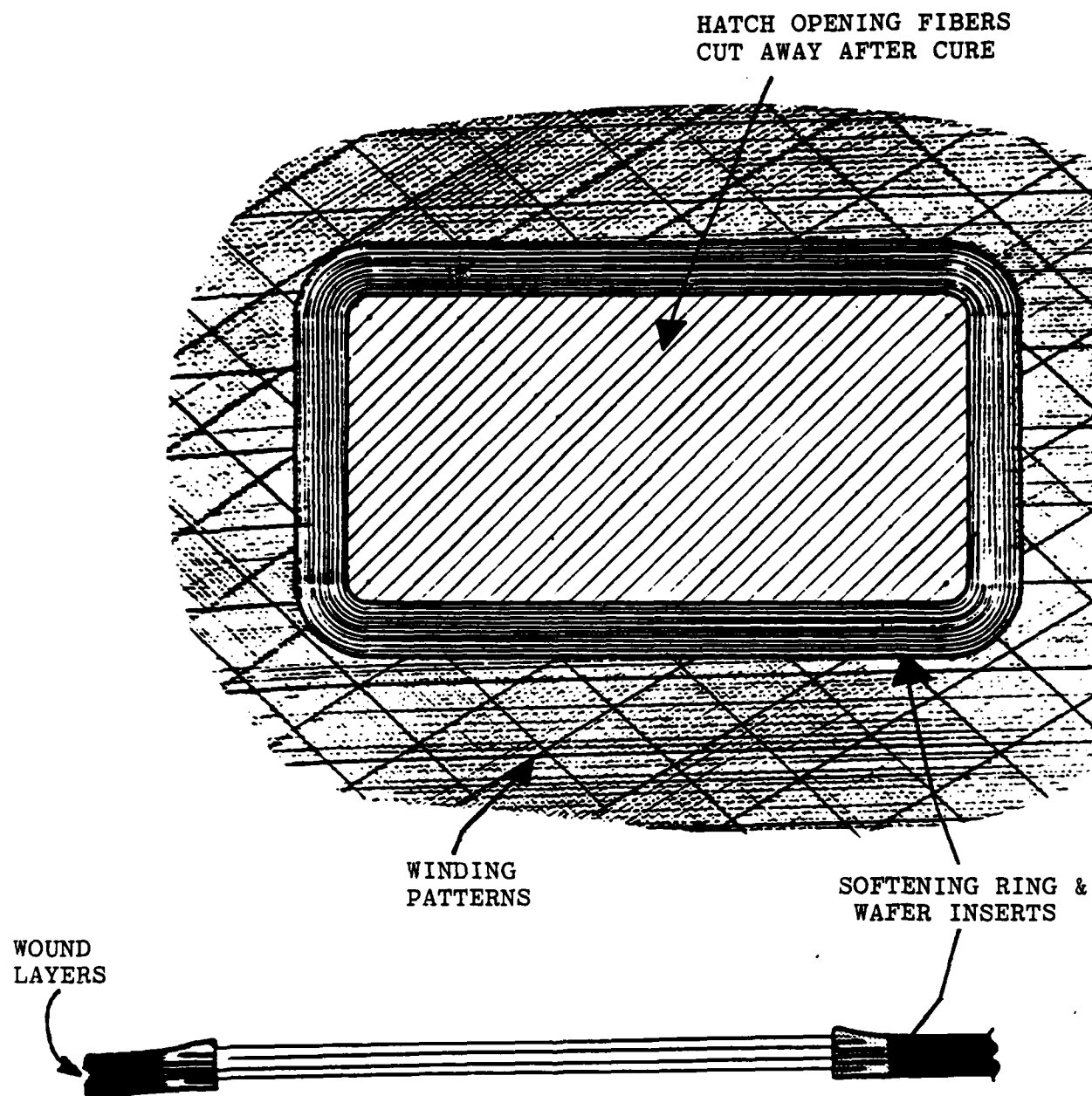
WOUND
LAYERS

Figure 25.    Deck Opening Reinforcement

REMOVABLE PIN IN
MANDREL

HULL

SECTION

FIBERS DEFLECTED AROUND PIN

FIBER BAND

OPENING

FIGURE 26.    SMALL OPENINGS WOUND IN PLACE

INSERT

OUTER OR INNER HULL

REMOVABLE PIN IF ON
OUTSIDE OF HULL

FIBERS DEFLECTED AROUND PIN
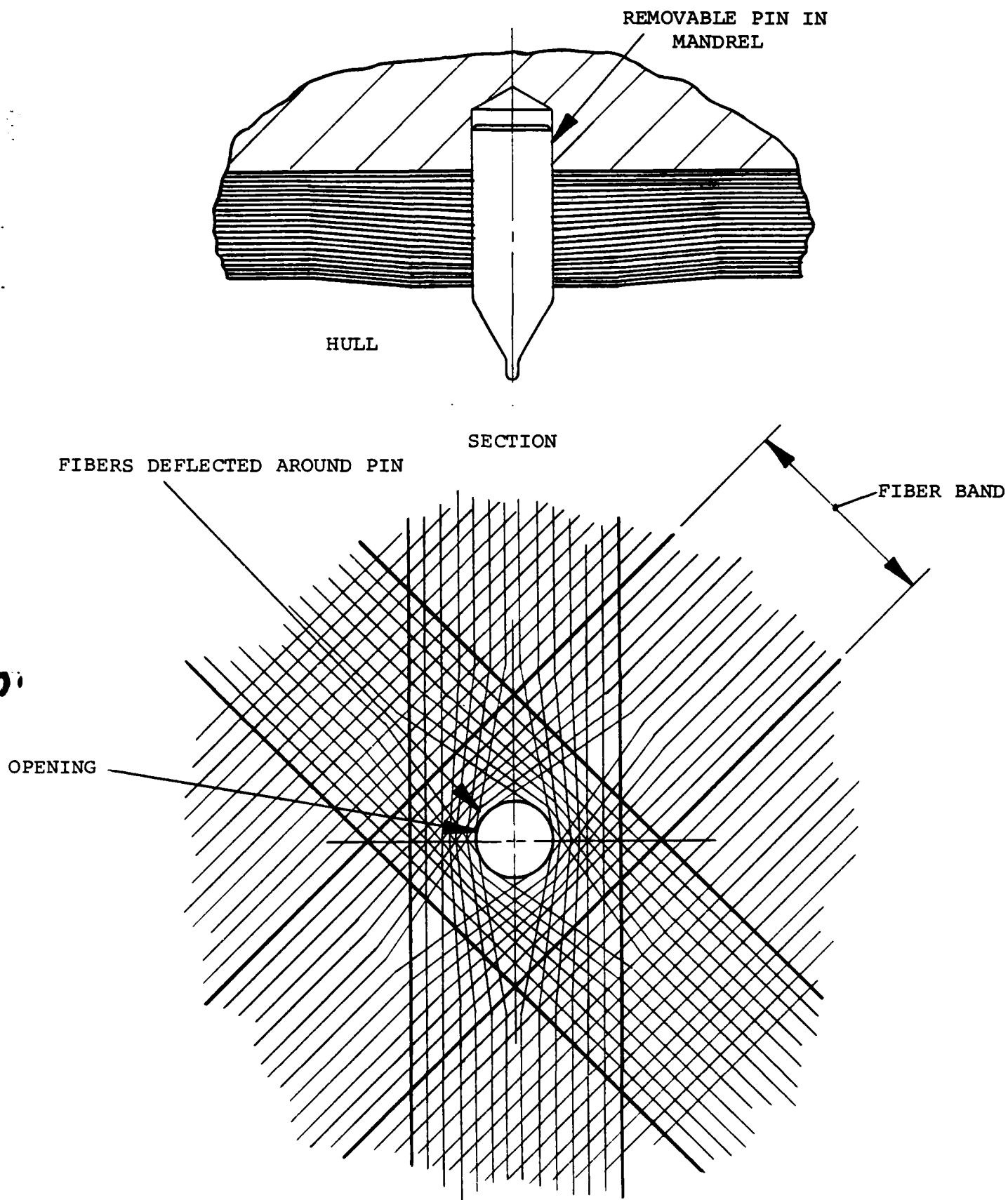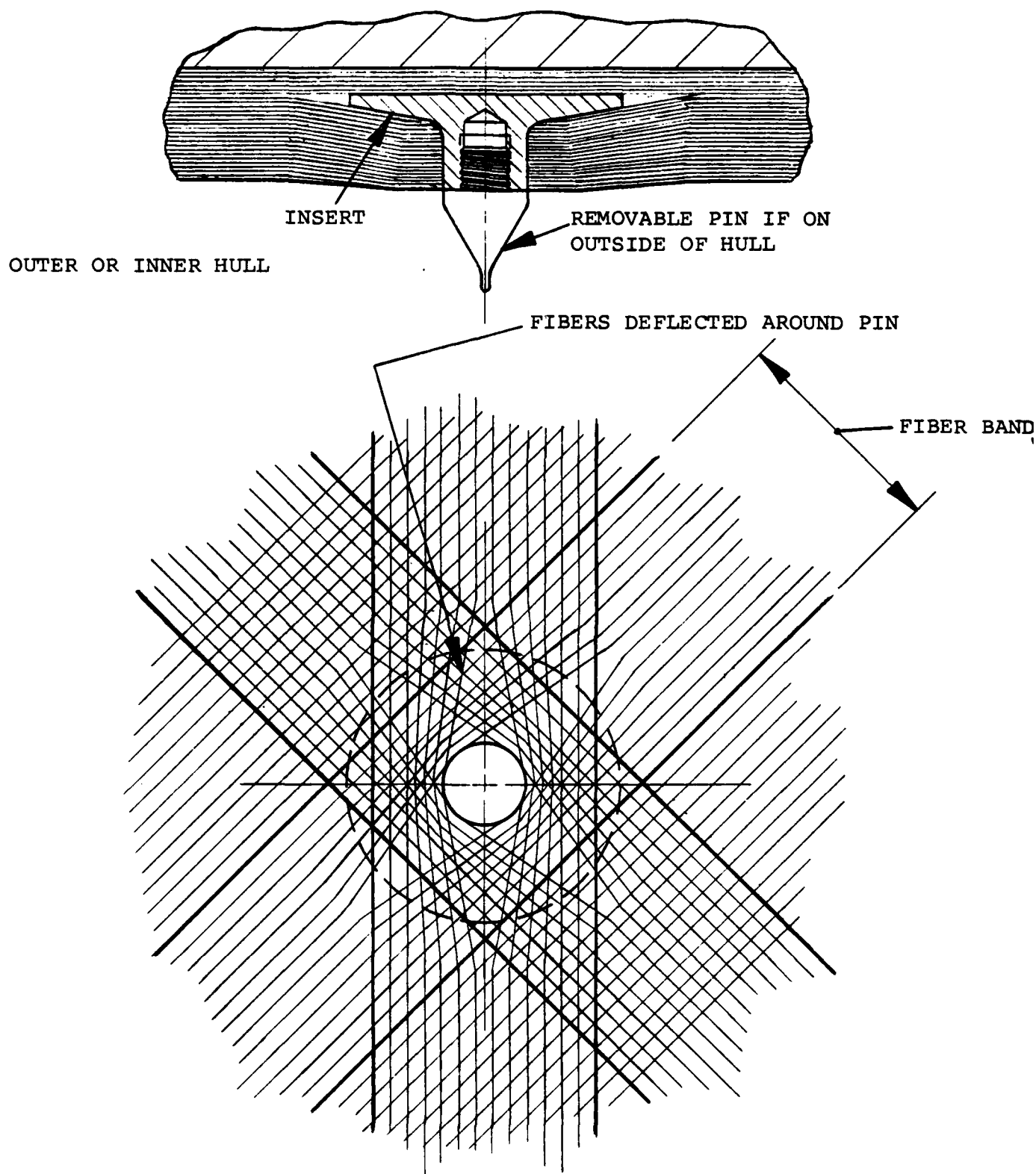
FIBER BAND

FIGURE 27.  SMALL INSERTS WOUND IN PLACE

This will assure that there are fibers near all portions of the opening. After cure, the inserts can be removed by drilling or by being driven out with a punch.

## 4.2 Frame Structures

### 4.2.1 Integral Frames

Two suggested frame structures are shown in Figure 28. The frame in (A) of Figure 28 is made integral with the hull during winding. The succeeding wound layers are programmed to enter the ring cavity. In between groups of these layers, an adhesive filler is placed, or pre-cast fiber sections are put in place. Circumferential windings with adhesive filler can be used at each frame structure to present a smooth surface for the outer wound layers of the hull. Bulkheads can be attached to these frames.

Frame (B) of Figure 28 is made by winding most hull layers into a cavity. Prior to the final hull wound layers, the remaining cavity is filled with circumferential windings cured as they are being placed. The remaining cavity may also be filled completely or partially, using pre-cast fiber sections, depending upon the strength and stiffness requirements. Bulkheads can be attached to these frames.

### 4.2.2 Separately Wound Frames

The frames in (A) and (B) of Figure 29 are pre-made and then wound-in during hull fabrication. It is proposed that a quantity of shallow frames could be integrally wound as shown. These shallower frames will hold the deep frames captive, and can be just sealed to the hull or bonded during the winding

57

BULKHEAD MOUNTING
IF APPLICABLE

FRAME

CIRCUMFERENTIAL WINDINGS

WOUND LAYERS OF
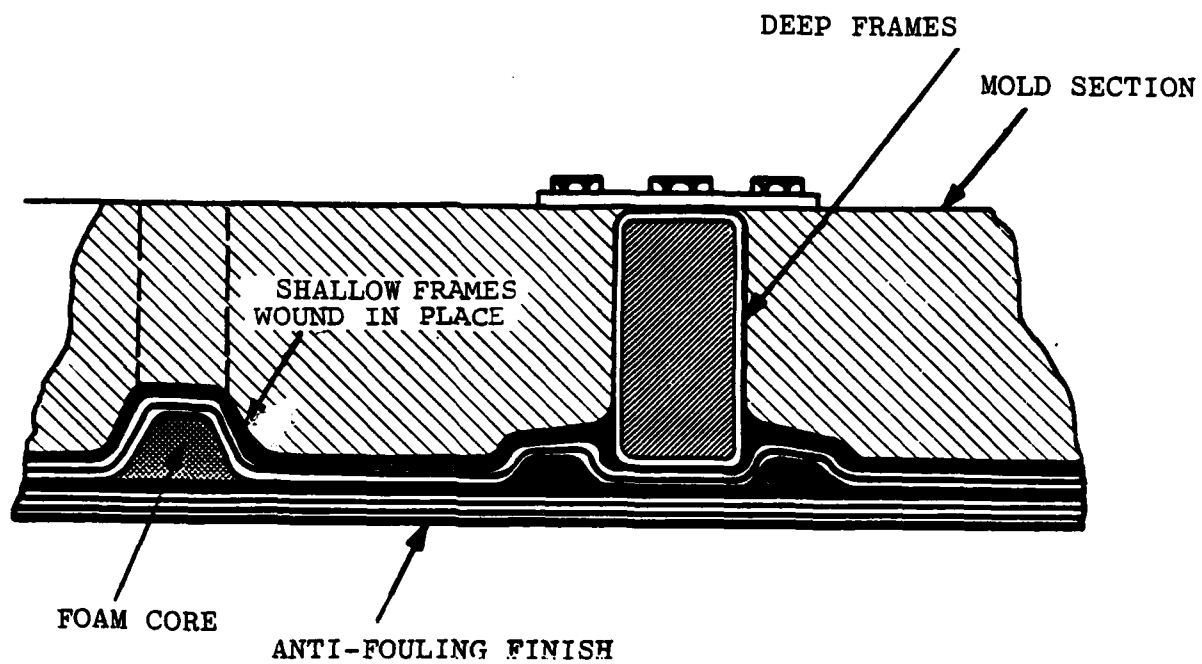VARIOUS ANGLES

HULL OUTER SURFACE

(A)

BULKHEAD MOUNTING

CIRCUMFERENTIAL WINDINGS

FRAME

WOUND LAYERS OF
VARIOUS ANGLES

HULL OUTER SURFACE

(B)

Figure 28.   Integrally Wound Hull Frames

58

DEEP FRAMES

MOLD SECTION

SHALLOW FRAMES
WOUND IN PLACE

FOAM CORE

ANTI-FOULING FINISH

(A)

BULKHEAD BOLT-IN

FRAME HOLDER

DEEP FRAME

SHALLOW
FRAME
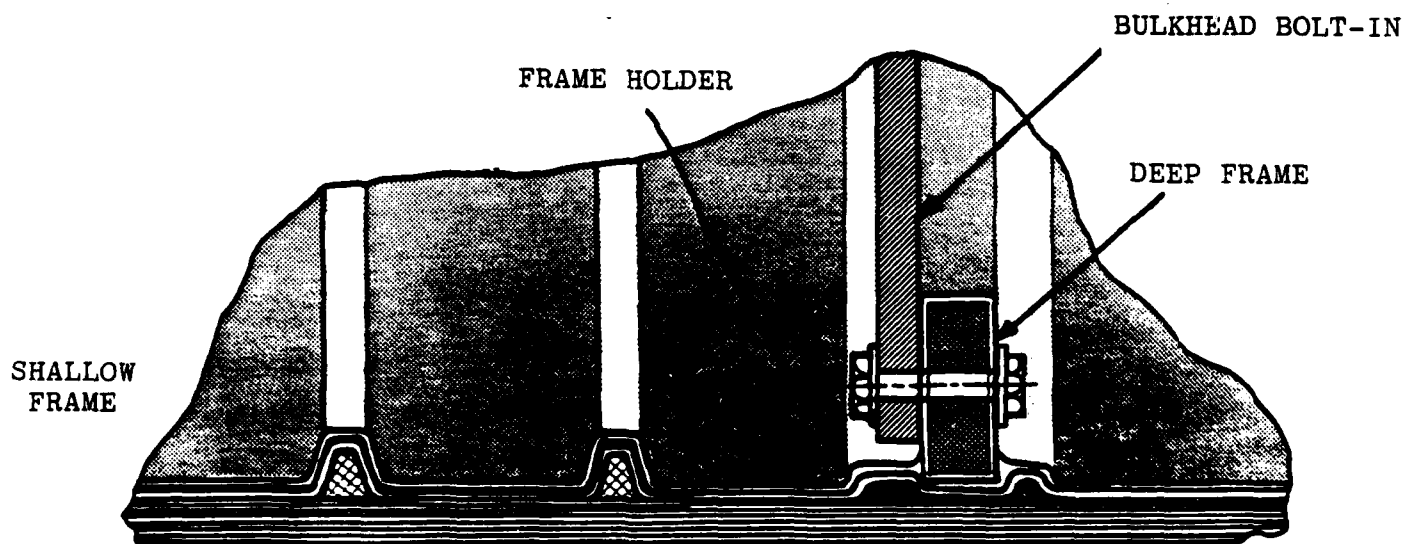
(B)

Figure 29.   Separately Wound Hull Frames

59

as desired.  The deep frames can have bulkheads bolted to them.

### 4.2.3  Hull Aft End Attachment (See Figure 30.)

The aft end of the hull is lightly loaded.  The possibility of
having a removable transom is attractive for both fabrication and
servicing of the completed hull.  During fabrication, mandrel
support is made simpler without a transom, and fiber placement
is easier.  An open aft end permits another entry for gear, in
addition  to the deck hatches.

The system shown in Figure 30 is that of winding filaments around
inserts during hull winding.  It has been used on rocket tubes
where a front closure is bolted to a filament wound tube where
the tube I.D. is constant, and fibers cannot be wound over the
end to take the tensile loads.  In the example shown, bolts
and seals are used through the holes for the attachment of
transom and hull.  Permanent or removable sealing compounds
can be used during the assembly of this joint.

### 4.3  Anti-Fouling Finish

It is proposed that the anti-fouling finish selected should be
of a thixotropic plaster-like consistency.  This material would
be applied in a manner similar to that used for plaster walls,
using trowel-like tools.  This material would be applied during
the last of the winding, and would be compatible with the resin
for good bonding.  Cure should be within a few hours.  Struc-
turally, the material would have to withstand the hull strains
and environment.  An alternate application method might be that
of spraying a high viscosity version of the anti-fouling finish.

ATTACHMENT HOLES - AN EXTENSION OF HUL WINDING FIBERS

AFT END REMOVEABLE TRANSOM

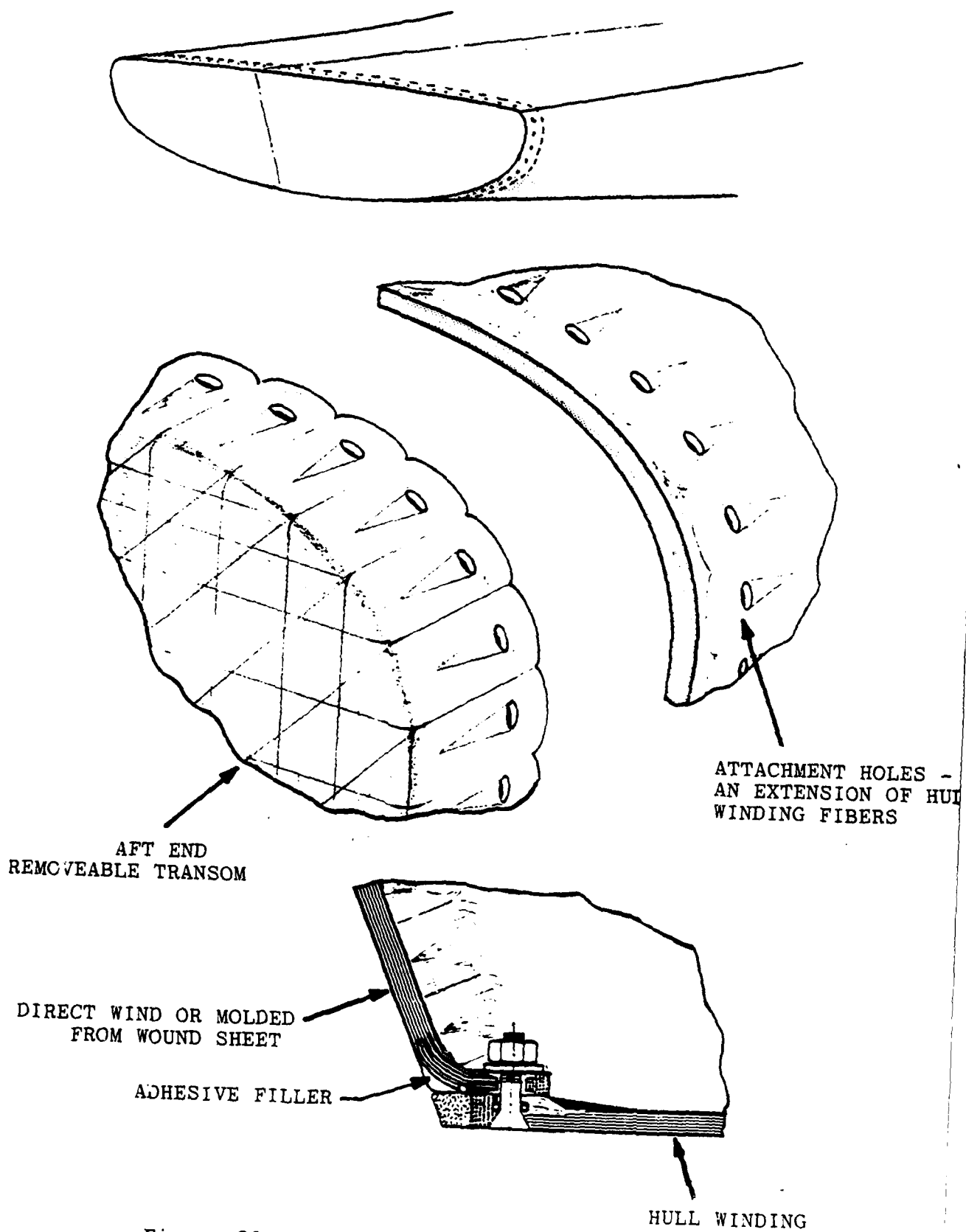DIRECT WIND OR MOLDED FROM WOUND SHEET

ADHESIVE FILLER

HULL WINDING

Figure 30.    Hull Aft End Attachment

61

## 4.4  Repair of Thick-Wall Structures

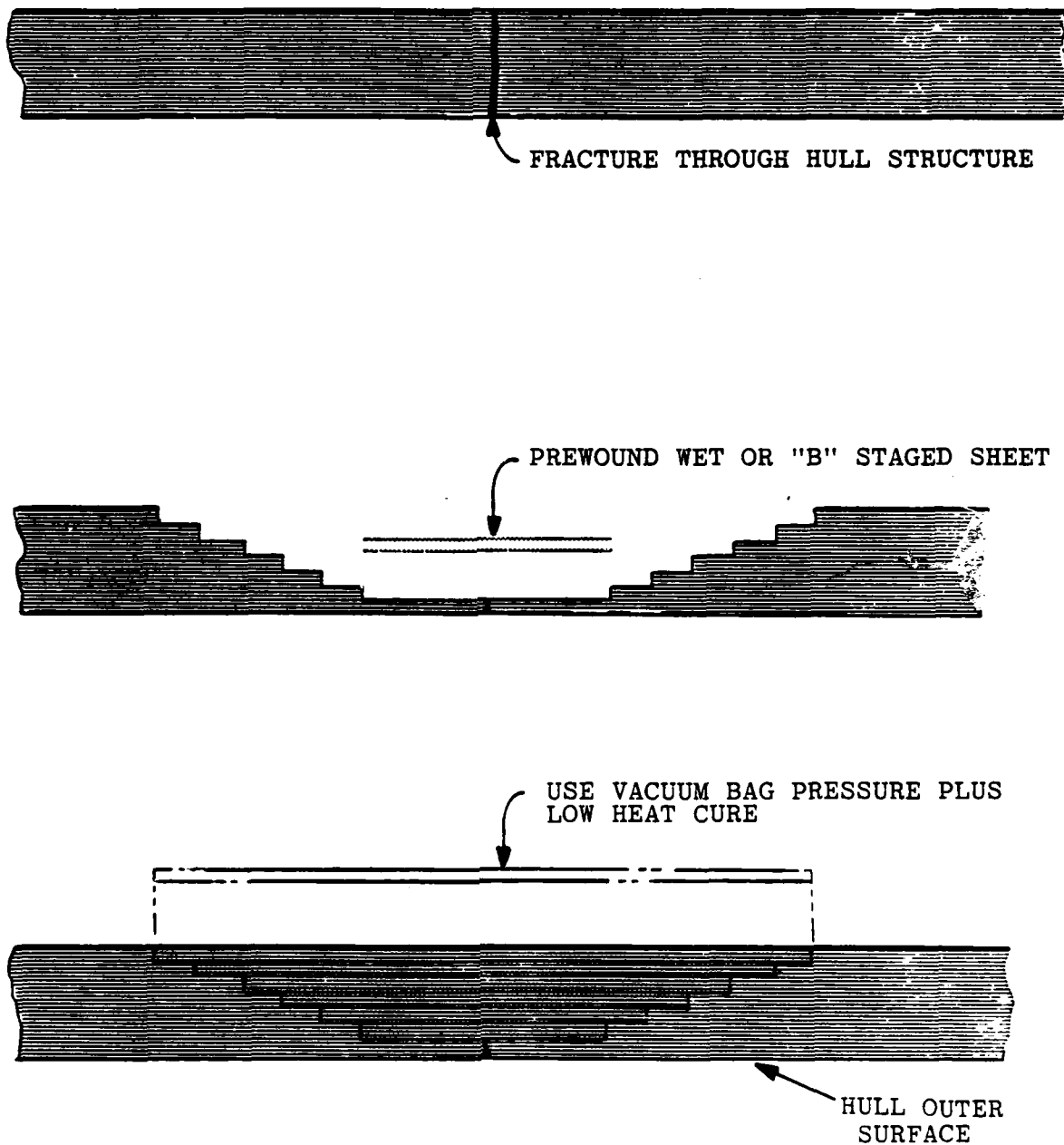Refer to Figure 31.  This is an in-service need to recover performance capabilities.

FRACTURE THROUGH HULL STRUCTURE

PREWOUND WET OR "B" STAGED SHEET

USE VACUUM BAG PRESSURE PLUS
LOW HEAT CURE

HULL OUTER
SURFACE

Figure 31.  Thick Wall Repairs

62

The technique shown is the one that is used for high performance composites, such as those used in aircraft, where close to the original undamaged performance must be attained with field repairs.

It is relatively easy to grind layers of the hull and to step grind to the surface between layers. The change in fiber direction between each layer is quite distinct. Similarly, the steps can be made by grinding to smaller areas toward the outer portion of the hull, as shown. Pre-wound material in cold storage or wound near site can be used in its uncured state for patching. Each layer of patching material should be cut to match the ground shape. It may be necessary to patch the crack or damaged area to prevent water seepage on the ground surfaces. The patching surfaces must be dry and free of grease or dust. The resin selected can be an epoxy having a tolerance for water. After layering, vacuum bag pressure can be applied, with room temperature cure, or with a heated blanket. Ultrasonic or other suitable checks of the layer interfaces should be made.

SECTION 5

ANALYSIS OF NON-REPRESENTATIVE WINDING

CONDITIONS DURING THE WINDING TRIALS


5.1   Introduction

As much as possible, the winding trials described in Section 2
and 3 were carried out in such a way as to incorporate the
conditions that would be present when winding a ship
hull of 200-foot length.  For example, fiber tension was main-
tained at approximately four ounces per end during the trials
so that fiber packing forces developed on the 1/48-scale
mandrels would equal those developed on a full-sized mandrel
under tension of 10 lbs per end.

It was not considered practical or necessary, however, for all
study conditions to conform to the anticipated full-size
winding conditions.  Four non-representative conditions were
permitted, none of which was considered to detract from the
accuracy and completeness of the feasibility study.  These
four winding conditions are discussed in the following sub-
sections.


5.2   Construction and Support of the Mandrel

No attempt was made during the study to construct 1/48-scale
mandrels incorporating preformed bulkheads and other structural
elements.  While mandrels of such construction would almost
certainly be used in the production of full-size windings,

they were not required for the analysis of stable fiber paths.
There was also no attempt made to mount and support the 1/48-
scale mandrels with a retractable support mechanism, such as
would probably be used on full-size, non-rotating mandrels.  Due
to the size and weight involved, the foam mandrels used in the
trials did not require such a mechanism.   In any case, the feasi-
bility of using retractable supports has been demonstrated else-
where and was, therefore, not an issue requiring study or demon-
stration.

5.3    Control of the Filament Band

5.3.1    Band Flattening Devices

During the winding trials, no attempt was made to control the
filament band between the delivery eye and the mandrel.   On
full size windings, the distance between the eye and the point
at which the filament band contacts the mandrel would be greater
than the distance exhibited during the 1/48-scale trials.   At
such distances, a band flattening device would be required in
order to maintain the rectangular cross-section of the band and
the uniform distribution of fibers and resin within the band.
The feasibility of using band flattening devices has been demon-
strated elsewhere and was, therefore, not an issue requiring study
or demonstration.

5.3.2    Devices for Varying Bandwidth

As indicated in Section 2, computer control of the rotating eye
capability was eliminated during the study so that a vertical
motion capability could be computer controlled instead.   No

attemps were made, therefore, to vary the width of the filament

band during the winding process.    When stable filament paths

were less than one bandwidth wide, fibers were overlapped onto

previously placed fibers in order to prevent slippage.    During

full size windings, overlapping of adjacent bands of fibers

could be eliminated by the use of a computer capable of controll-

ing both vertical motion and a rotating eye.

> NOTE - The use of a rotating eye causes the thickness
> of the filament band to vary inversely with the
> width of the band.    If variations in band thick-
> ness are considered objectionable for full-size
> hulls, independent control of band thickness
> could be achieved by varying the number of rovings
> being wound as the eye rotates.    The feasibility
> of picking up rovings automatically is currently
> under investigation.    The dropping of fibers has
> been demonstrated and used on prototypes.

## 5.4    Rate of Mandrel Rotation

During a full-size winding, the rate of mandrel rotation would be

reduced by the scaling factor.    With a non-rotating mandrel it

might be zero.    Reducing the rate of rotation would tend to enable

resin to flow on the mandrel surface to a greater degree than was

possible during the 1/48-scale windings.    It would also allow the

thick uncured mass of windings to sag and move away from the mandrel.

No attempt was made during the study to rotate the 1/48-scale

mandrels at the slow speed required for a full-size winding.

66

Nor was a slow rate of rotation used during production of the full-size hull sections. The feasibility of controlling resin flow at such rates of rotation and sagging of the windings at zero to full rpm's has been established elsewhere during in-process curing, and therefore was not an issue requiring study or demonstration.

## 5.5    Production Time

No attempt was made during the study to wind a 1/48-scale mandrel for a continuous period of 22 hours, although a full-size winding is expected to require that much fabrication time. The feasibility of working with resins for such long periods is well established and, therefore, was not an issue requiring study or demonstration.

# SECTION 6

## CONCLUSIONS AND RECOMMENDATIONS

### 6.1    Conclusions

The conclusion of this study is that it is feasible to filament
wind large ship hulls.  This conclusion is warranted by the
findings described in Sections 2, 3, and 4.  These findings
are as follows:

- Fibers can be wound successfully on a hull-shaped
  mandrel.

- Walls of the thickness required for large ship
  hulls can be wound successfully.

- Non-representative conditions that occurred during
  the winding trials do not diminish the accuracy
  or completeness of the feasibility study.

### 6.2    Recommendations

Although this report has established the feasibility of producing
large ship hulls with the filament winding process, much work
remains to be done before the actual production of such hulls
can be undertaken.  In particular, structural elements of the
hull need to be optimized, as do the mechanical and control systems
of the machinery required for winding a hull of 200-foot length.

It is, therefore, recommended that a 30-foot long ship hull be designed, fabricated, and evaluated. This should be followed by a 30-ft long full-size section of a large ship hull so that the hull design and full-sized manufacturing equipment can be demonstrated before the Navy makes a financial and strategic commitment to the production of complete filament wound hulls.

Such effort should be directed toward the accomplishment of the following objectives:

- Establish rib, bulkhead, and hull thicknesses and geometries, as well as the required surface charac-teristics for a full size ship hull

- Optimize designs for hatch and other type openings and attachments

- Develop a mandrel system incorporating pre-made portions, thereby reducing post-fabrication fitting time

- Design machinery to support a full size, hull-shaped mandrel

- Design following pressure pads to hold fibers against areas of negative curvature

- Modify existing computer software to permit control of the carriage, crossfeed, rotating eye, and verti-cal motion of the fiber delivery system

- Design a fiber delivery system that incorporates a band flattening system for maintaining band integrity on large hull windings

69

- Select resin formulations that provide in-process curing

- If precise control of hull thickness is determined to be
  desirable, develop a system for automatically varying
  the number of filament rovings being placed on the mandrel
  at any given time

- If surface characteristics of filament would structures
  are considered less than optimum for hull applications,
  then surface finishing materials and techniques should
  be developed and classified for use in hull windings.

# A P P E N D I X

- Material Properties
- Hull Thickness Calculations
- Glossary

TABLE A-1

## MATERIAL PROPERTIES

| Laminate | Material | Modulus E $(10^6$ psi) | Tension Strength, $F_{tu}$ $(10^3$ psi) | Compressive Strength, $F_{cu}$ $(10^3$ psi) |
|---|---|---|---|---|
| (25% $0^o$/25% $90^o$/50% $45^o$)[1] | E-glass/epoxy | 2.74 | 45.6 | 41.0 |
| (25% $0^o$/25% $90^o$/50% $45^o$) | Graphite/epoxy | 7.50 | 68.0 | 52.0 |
| (70% $0^o$/10% $90^o$/20% $45^o$)[2] | E-glass/epoxy | 4.70 | 78.2 | 70.0 |

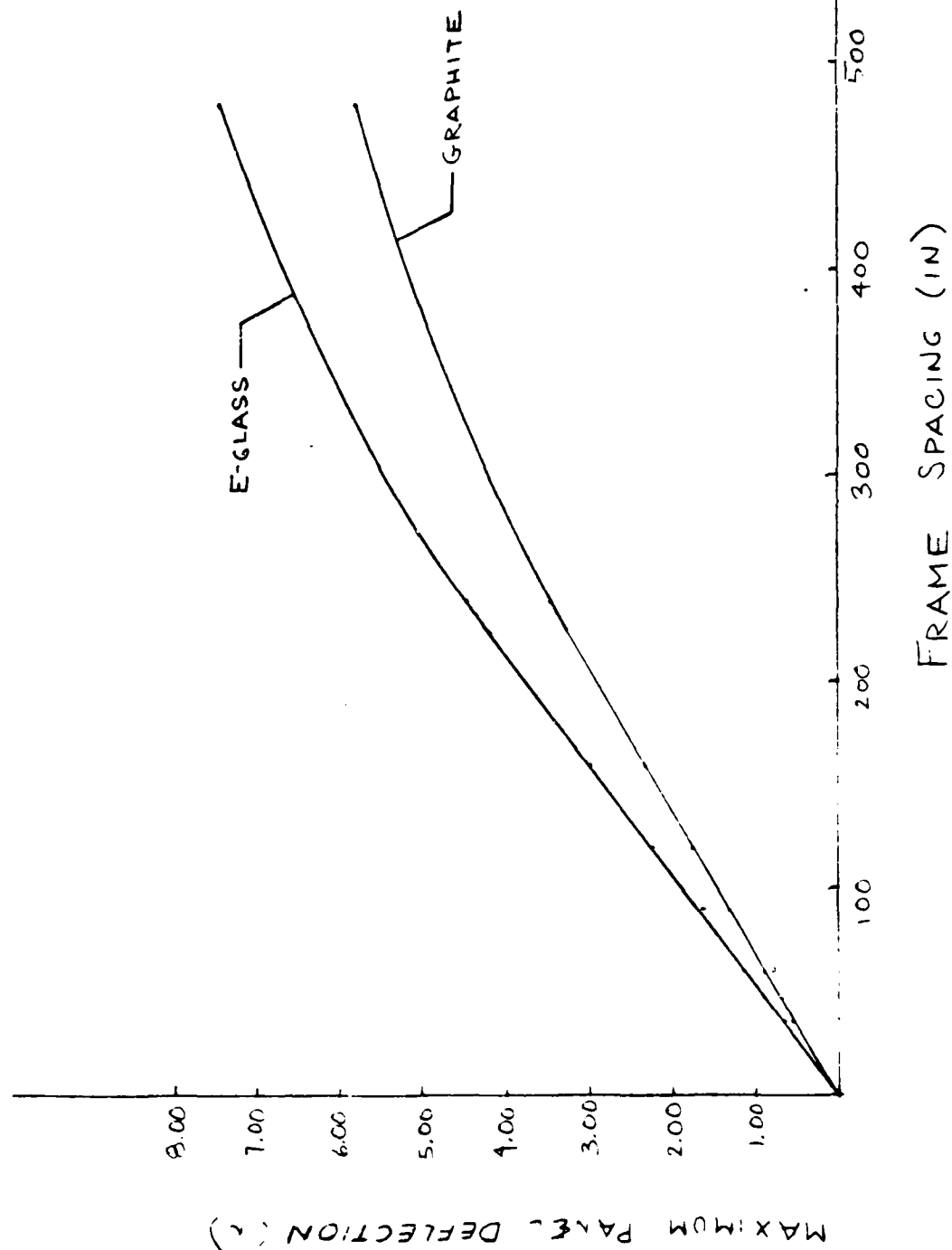(1) Layup is referred to as quasi-isotropic.

(2) Layup for intermediate frames.

A-1

FIGURE A-1
REQUIRED HULL LAMINATE THICKNESS
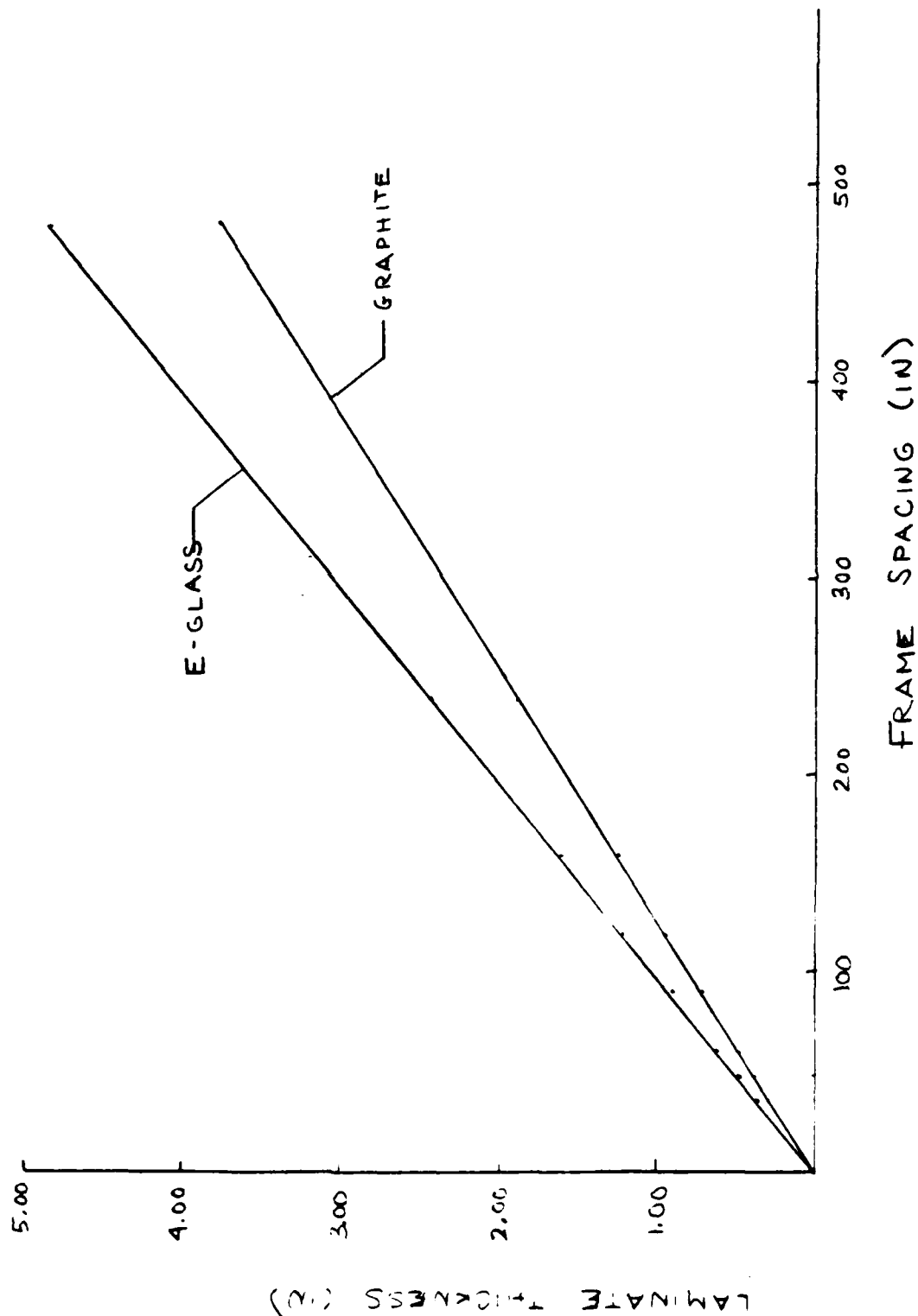
FIGURE A-2
MAXIMUM HULL DEFLECTION

GRAPHITE

E-GLASS

FRAME SPACING (IN)

MAXIMUM PANEL DEFLECTION (IN)

9.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00

100   200   300   400   500

A-3

Figure A-3
Required Deck Laminate Thickness
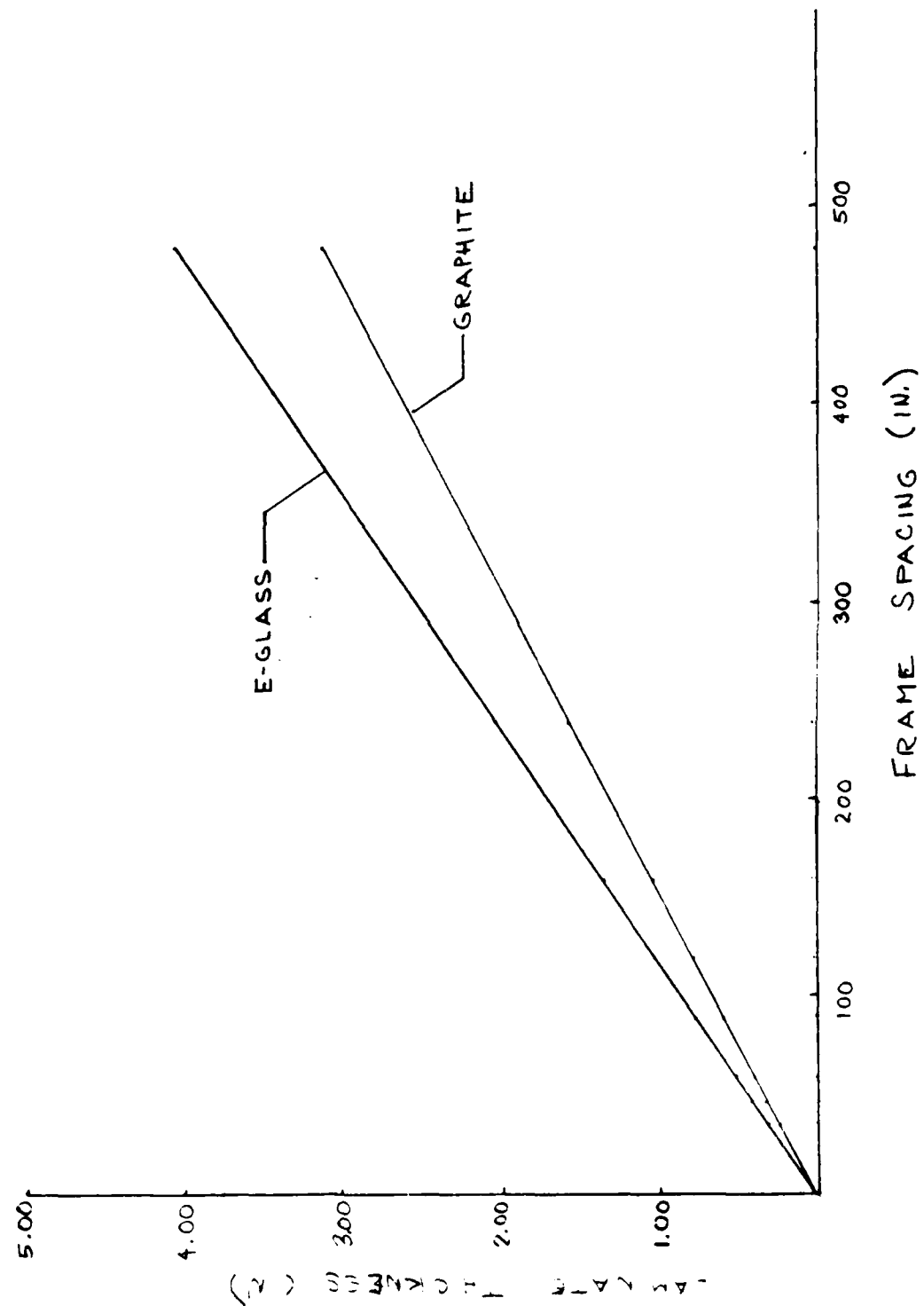
FIGURE A-4
MAXIMUM DECK DEFLECTION
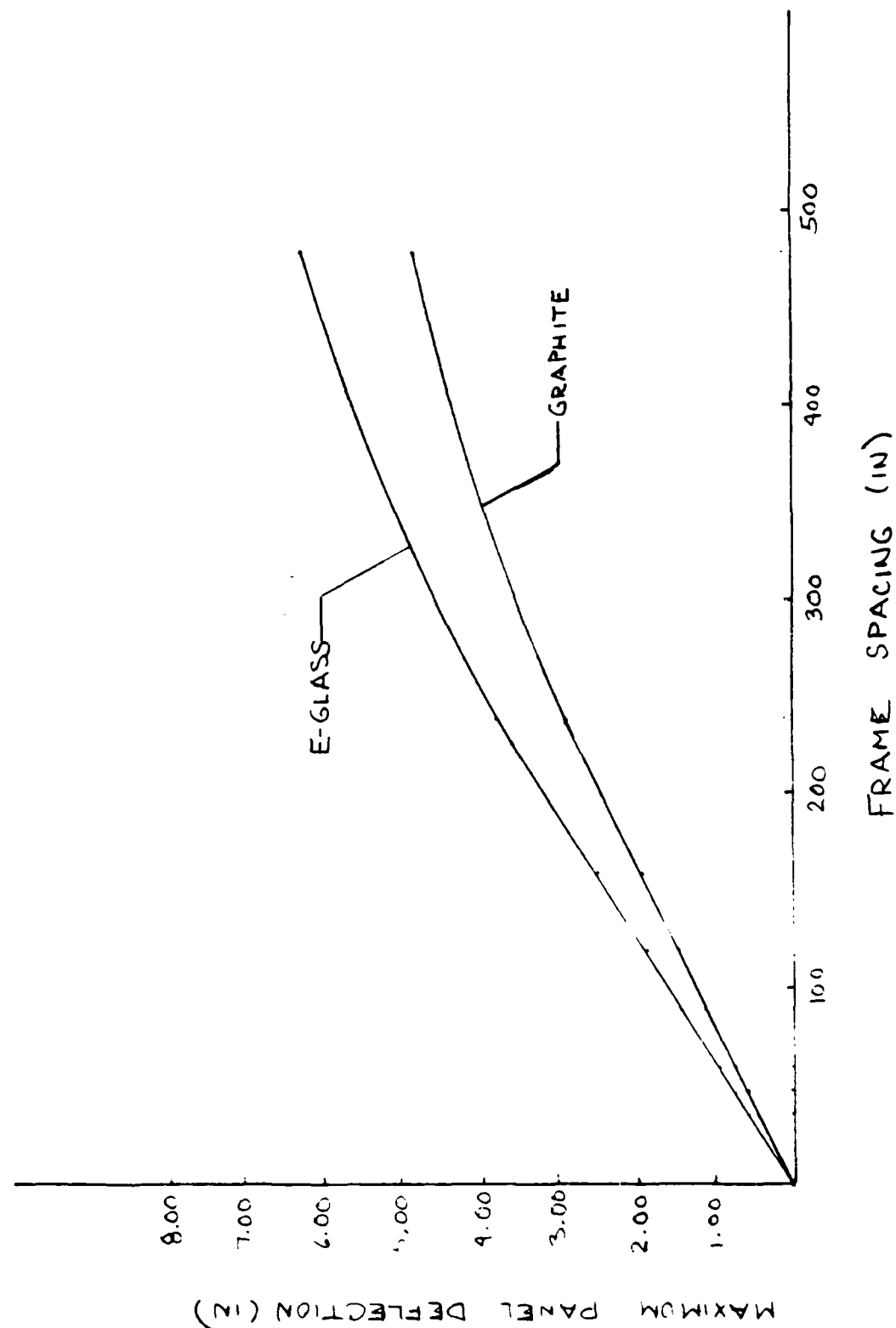
FIGURE A-5
STRUCTURAL WEIGHT OF AN E-GLASS BOAT



(1) WEIGHT OF 1 SEGMENT
480 INCHES IN LENGTH ×
480 INCHES WIDE

FRAME SPACING (IN)

TOTAL STRUCTURE WEIGHT ($10^3$ LB) (1)
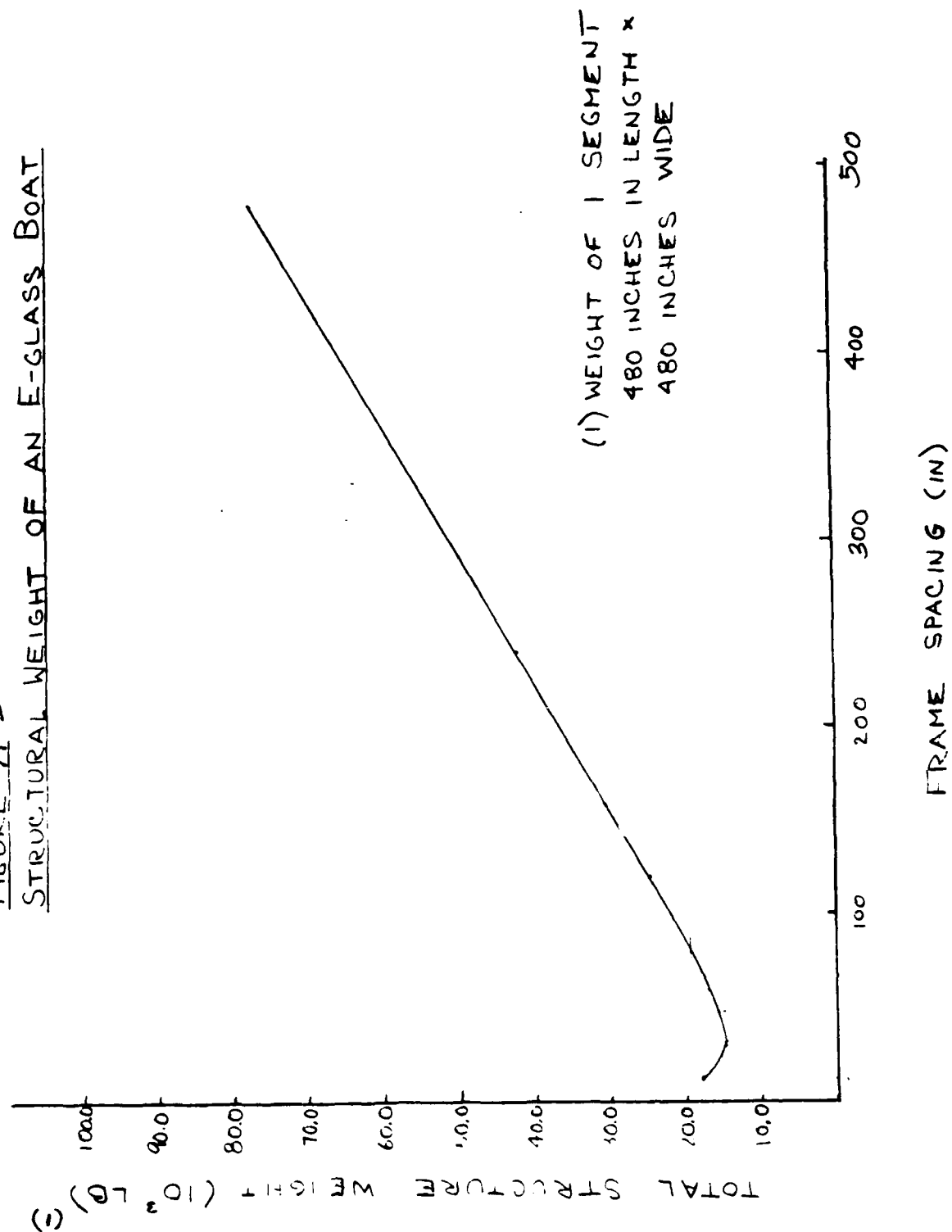
# REFERENCES

(1)   McClean-Anderson Drawing 3-3536.

(2)   Letter from J.L. McLarty to Derek Yates, dated October 17, 1980.

(3)   Formulas for Stress and Strain, R.J. Roark, Fourth Edition,
      McGraw-Hill Book Company, New York, 1965.

(4)   Analysis and Design of Flight Vehicle Structures, E.F. Bruhn,
      Tri-State Offset Company, 1973.

## PANEL STRESS/DEFLECTION

THE RELATIONSHIP BETWEEN MAXIMUM STRESS AND LAMINATE THICKNESS FOR A FLAT, RECTANGULAR PANEL WITH FOUR FIXED EDGES, IS

$$S = \frac{C_1 E t^2}{b^2} \quad (1) \qquad (REF. 3, P. 246)$$

WHERE

$S$ = MAXIMUM STRESS (PSI)
$E$ = YOUNG'S MODULUS (PSI)
$t$ = LAMINATE THICKNESS (IN)
$b$ = SMALLER PANEL DIMENSION (IN)

MAXIMUM DEFLECTION IS RELATED TO LAMINATE THICKNESS AS FOLLOWS:

$$\Delta = C_2 t \quad (2) \quad (REF. 3, P. 246)$$

WHERE

$\Delta$ = MAXIMUM DEFLECTION (IN)
$t$ = LAMINATE THICKNESS (IN)

THE COEFFICIENTS $C_1$ AND $C_2$ ARE FUNCTIONS OF THE PANEL ASPECT RATIO $(a/b)$ AND THE DIMENSIONLESS QUANTITY $\left( \frac{w b^4}{E t^4} \right)$. THE LIMITING VALUE OF THE DIMENSIONLESS QUANTITY IS ABOUT 250. FOR VALUES LARGER THAN 250, THE CALCULATED STRESSES AND DEFLECTIONS BEGIN TO DIVERGE FROM EXPERIMENTALLY

DETERMINED VALUES. THEREFORE, THIS QUANTITY IS SET EQUAL TO 250 AND THE REQUIRED LAMINATE THICKNESS COMPUTED:

$$t_{REQD} = \left( \frac{wb^4}{E \times 250} \right)^{1/4}$$

WHERE

W = APPLIED UNIFORM LOAD (PSI)

ONCE $t_{REQD}$ HAS BEEN CALCULATED, PANEL DEFLECTION AND LAMINATE STRESS ARE DETERMINED FROM EQUATIONS (2) AND (1), RESPECTIVELY.

RESULTS OF THESE CALCULATIONS ARE TABULATED BELOW:

## HULL PANELS

| FRAME SPACING b (IN) | E-GLASS $t_{REQD}$ (IN) | $\Delta_{MAX}$ (IN) | GRAPHITE $t_{REQD}$ (IN) | $\Delta_{MAX}$ (IN) |
|---|---|---|---|---|
| 12 | .121 | 0.23 | .094 | 0.18 |
| 24 | .241 | 0.45 | .188 | 0.35 |
| 36 | .362 | 0.67 | .282 | 0.52 |
| 48 | .483 | 0.90 | .375 | 0.70 |
| 60 | .603 | 1.12 | .469 | 0.87 |
| 90 | .905 | 1.68 | .704 | 1.31 |
| 120 | 1.206 | 2.24 | .938 | 1.75 |
| 160 | 1.609 | 2.99 | 1.251 | 2.33 |
| 240 | 2.413 | 4.49 | 1.876 | 3.49 |
| 480 | 4.826 | 7.43 | 3.752 | 5.78 |

## DECK PANELS

| FRAME SPACING b (IN) | E-GLASS $t_{REQD}$ (IN) | $\Delta_{MAX}$ (IN) | GRAPHITE $t_{REQD}$ (IN) | $\Delta_{MAX}$ (IN) |
|----------------------|--------------------------|----------------------|---------------------------|----------------------|
| 12  | .102  | 0.19 | .079  | 0.15 |
| 24  | .203  | 0.38 | .158  | 0.30 |
| 36  | .305  | 0.57 | .237  | 0.44 |
| 48  | .406  | 0.76 | .316  | 0.59 |
| 60  | .508  | 0.94 | .395  | 0.73 |
| 80  | .761  | 1.42 | .592  | 1.10 |
| 120 | 1.015 | 1.89 | .789  | 1.47 |
| 160 | 1.353 | 2.52 | 1.052 | 1.96 |
| 240 | 2.029 | 3.77 | 1.578 | 2.93 |
| 480 | 4.059 | 6.25 | 3.155 | 4.86 |

## FRAME DIMENSIONS

FRAMES ARE TREATED AS A GROUP OF BEAMS FIXED AT EACH END AND LOADED BY A UNIFORM RUNNING LOAD, P. THE LENGTH OF EACH BEAM IS APPROXIMATELY 480 INCHES, AS SHOWN.
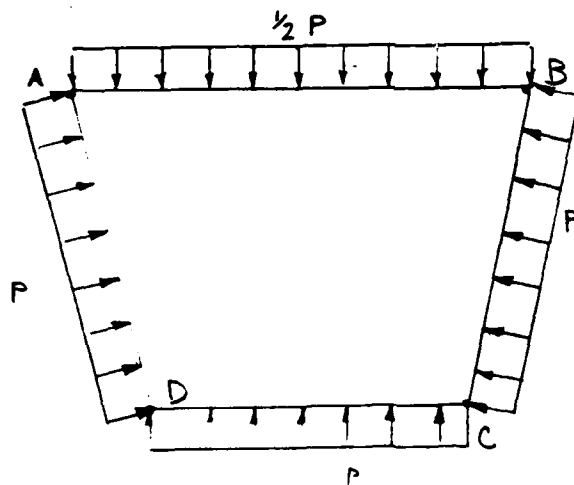


BOAT CROSS-SECTION
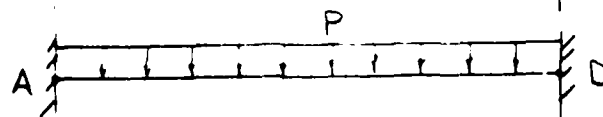


$P = 7.0$ PSI. $\times$ b WHERE b = FRAME SPACING

DEFLECTION AND STRESS FOR THE FIXED-FIXED

BEAM A-D ARE GIVEN BY

$$\Delta = \frac{PL^4}{384\,EI}$$

$$\sigma = \frac{Mc}{I} = \frac{PL^2c}{12\,I}$$

MAXIMUM DEFLECTION SHOULD BE LIMITED TO

$1/100$ L AND MAXIMUM STRESS TO MAXIMUM

MATERIAL COMPRESSIVE STRENGTH. FOR AN E-GLASS

LAMINATE WHICH IS 70% UNIDIRECTIONAL FIBER,

$$F_{cu} = 70,000 \text{ PSI}.$$

$$E = 4.70 \times 10^6 \text{ PSI}.$$

SO,

$$\frac{L}{100} = \frac{(7.0 \cdot b)(L)^4}{384\,(4.7 \times 10^6)\,I}$$

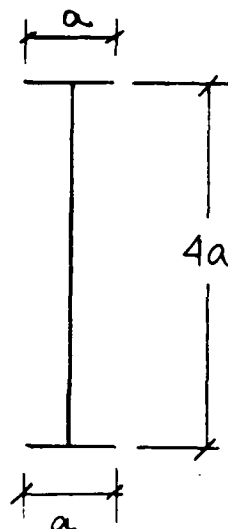$$I_{REQD} = \frac{700 \times (480)^3}{384\,(4.7 \times 10^6)}\,b$$

$$I_{REQD} = 42.9\,b$$

AND

$$\left(\frac{I}{c}\right)_{REQD} = \frac{7.0\,b\,(480)^2}{12 \times 70000} = 1.92\,b$$

ASSUME THE FOLLOWING FRAME CROSS-SECTION:



$$t = a/10$$

$$A = 0.6a^2$$

$$I = \tfrac{1}{12}(.1a)(4a)^3 + 2(0.1a^2)(2a)^2 = 1.333a^4$$

$$c = 2a$$

$$I = 1.333a^4 = 42.9\,b$$

$$a_{REQD} = (32.18\,b)^{\frac{1}{4}} \quad \text{(DEFLECTION CRITERIA)}$$

$$(I/c) = 0.667\,a^3 = 1.92\,b$$

$$a_{REQD} = (2.88b)^{\frac{1}{3}} \quad \text{(STRENGTH CRITERIA)}$$

FOR b LESS THAN 484.3 IN., THE DEFLECTION

CRITERIA IS MORE CRITICAL. THEREFORE, THE

DEFLECTION CRITERIA IS USED TO SIZE THE

FRAME.

## OPTIMUM FRAME SPACING

FRAME SPACING IS OPTIMIZED FROM THE STANDPOINT OF TOTAL STRUCTURAL WEIGHT.

$$a = (32.18\, b)^{1/4}$$

FRAME WEIGHT $= \rho A L$

$$= .07\ LB/IN^3\ (0.6\, a^2)(480\ IN.)$$

$W_f =$ FRAME WEIGHT $= 114.4\, b^{1/2}$

$\eta =$ NUMBER OF FRAMES $= 480\ IN/b$

$$\eta \cdot W_f = \frac{480}{b}\,(114.4\, b^{1/2}) = 54894/b^{1/2}$$

SKIN WEIGHT $= \rho A t_{sk}$

$$W_2 = .07\ LB/IN^3\ (480\ IN)^2\ (W/E \times 25c)^{1/4}\, b$$

$$W_2 = 162.16\, b$$

TOTAL STRUCTURAL WEIGHT $= W_2 + \eta W_f$

$$W_T = \frac{54894}{\eta b} + 162.16\, b$$

$\dfrac{dW_T}{db} = 0$    CORRESPONDS TO THE MINIMUM VALUE OF $W_T$.

$$\frac{dW_T}{db} = -\tfrac{1}{2}(54894)\, b^{-3/2} + 162.16 = 0$$

FROM THIS EQUATION, OPTIMUM FRAME SPACING IS

$$b^* = 30.6 \text{ IN.}$$

THE FOLLOWING TABLE SUMMARIZES COMPONENT WEIGHTS AND TOTAL WEIGHT AS A FUNCTION OF FRAME SPACING.

| FRAME SPACING b (IN) | HULL SKIN THICKNESS t (IN) | WEIGHT OF SKIN W (LB) | NUMBER OF FRAMES η | FRAME AREA A (IN²) | WEIGHT OF FRAMES η·Wf (LB) | TOTAL WEIGHT WT (LB) |
|---|---|---|---|---|---|---|
| 12 | .121 | 1950 | 39 | 11.8 | 15850 | 17800 |
| 24 | .241 | 3900 | 19 | 16.7 | 11210 | 15110 |
| 30 | .362 | 4865 | 15 | 18.6 | 10020 | 14890 |
| 48 | .483 | 7784 | 9 | 23.6 | 7923 | 15710 |
| 60 | .603 | 9730 | 7 | 26.4 | 7087 | 16820 |
| 80 | .864 | 12970 | 5 | 30.4 | 6138 | 19110 |
| 120 | 1.206 | 19460 | 3 | 37.2 | 5011 | 24470 |
| 160 | 1.609 | 25950 | 2 | 43.1 | 4340 | 30290 |
| 240 | 2.412 | 38920 | 1 | 52.7 | 3543 | 42460 |
| 480 | 4.826 | 77840 | 0 | — | 0 | 77840 |

CONSIDERING GRAPHITE-EPOXY LAMINATE FOR HULL
AND DECK PANELS, MAXIMUM PANEL THICKNESS IS GIVEN
BY

$$t_{sk} = \left( \frac{w \, b^4}{E \times 250} \right)^{1/4}$$

$$t_{sk} = \left( \frac{7.0}{7.5 \times 10^6 \times 250} \right)^{1/4} b = 7.82 \times 10^{-3} b$$

$$W_2 = \rho (A)(t_{sk})$$

$$W_2 = .056 \, LB/IN^3 \, (480)^2 (7.82 \times 10^{-3} b) = 100.85 \, b$$

FROM PAGE 7, THE WEIGHT OF ALL INTERMEDIATE
FRAMES IN A HULL SEGMENT 480" × 480", IS

$$\eta \times W_f = 54894 \, b^{-1/2}$$

AND TOTAL WEIGHT IS

$$W_T = 54894 \, b^{-1/2} + 100.85 \, b$$

THE MINIMUM VALUE IS FOUND IN THE SAME
MANNER AS THAT USED FOR THE ALL GLASS
STRUCTURE

$$\frac{dW_T}{db} = 0 = -\frac{1}{2} (54894) b^{-3/2} + 100.85$$

$$b^* = 42.0 \, IN.$$

$$W_T^* = 8680 + 4034 = 12,710 \, LB. \quad (MINIMUM \, WEIGHT)$$

# GLOSSARY OF TERMS

"A" Stage  -  An early stage in the preparation of some thermo-
setting resins in which the material is still soluble in
certain liquids and is fusible.

angle (winding angle or helix angle)  -  An acute angle formed
by the intersection of the band with the longitudinal
axis of the mandrel (see Figure A-6).

"B" stage  -  An intermediate stage in the reaction of some
thermo-setting resins in which the material swells when
in contact with certain liquids and softens when heated,
but may not entirely dissolve or fuse.

band (fiber)  -  The parallel rovings (or strands) placed side
by side for winding onto a mandrel (see Figure A-6).

bandwidth  -  The width of the band, measured perpendicular
to the band direction (see Figure A-6).

bridge (bridging or bridged fiber)  -  One or more band windings
that do not make complete contact with the mandrel due
to a reverse (concave) curvature of the mandrel along
a part of its length.

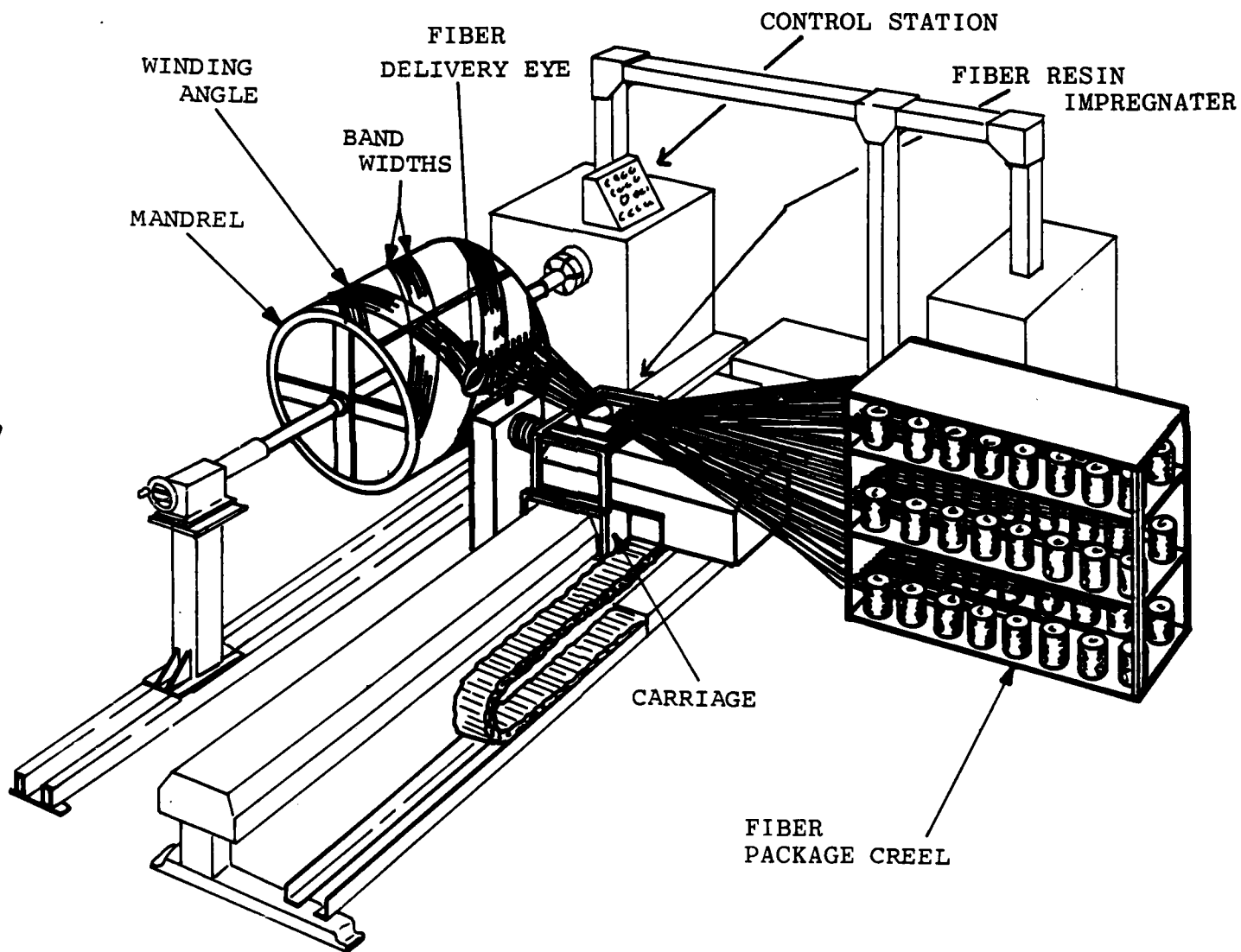"C" stage  -  The final, fully cured state of a thermosetting
resin.

Figure A-6. Typical Filament Winding Machine

carriage - The filament-delivery portion of a filament winding machine that traverses (parallel to) the longitudinal axis of the mandrel (see Figure A-6).

cloth - A fabric constructed by weaving (interlacing) fibers or filaments.

composite - A material containing two or more different substances; specifically, in filament winding, material consisting of continuous fibers reinforcing a suitable resin.

coupon - A cross-sectional sample of material specifically constructed to demonstrate feasibility of manufacture and for testing.

crossfeed - The filament-delivery portion of a filament winding machine that travels perpendicular to the longitudinal axis of the mandrel (see Figure A-6).

deck level (0, 1, 2, etc.) - The vertical subdivisions of a ship hull corresponding to the placement of designated decks (see Figure 1).

delivery eye - The part of the filament-delivery system of a filament winding machine that is closest to the mandrel, through which the band passes just prior to being wrapped around the mandrel. The eye is often capable of rotation through some angle (see Figure A-6).

eye   -   Same as delivery eye.

fiber (band)   -   A single homogeneous strand of material, either
natural or man-made, of extreme length.  Frequently used
synonymously with "band," although filament winding is
not normally done with single fibers.  (See "roving.")

filament   -   Single "hair" of fiber.

filament winding   -   A method of forming reinforced plastic
articles by winding continuous strands of resin-coated
reinforcing material (fibers or filaments) onto a mandrel.

hand lay-up   -   A method of forming reinforced plastic articles
by placing pieces of the reinforcement material, such as
cloth (which may or may not be preimpregnated with resin)
in a mold or over a form, and applying fluid resin to
impregnate and/or coat the reinforcement, followed by
curing of the resin.

helix angle (winding angle)   -   (See "angle.")

isotropic   -   A filament wound part in which strength properties
are equal in all directions.

laminate   -   General term for a filament wound structure.

mandrel  -  The form, either removable or non-removable,
         around which windings are wound (see Figure A-6).


mat  -  A fabric of glass or other reinforcing material cut
        to the contour of a mold, usually impregnated with
        resin just before or during the molding process.


quasi-isotropic  -  A filament wound part with fibers placed
         at several angles which are equal and in quantities
         which are equal.

         Example a.     25%    0° windings
                        25%    90° windings
                        25%    +45° windings
                        25%    -45° windings

         Example b.     25%    +22-1/2° windings
                        25%    -22-1/2° windings
                        25%    +67-1/2° windings
                        25%    -67-1/2° windings


resin  -  (Used interchangeably with "strand.")  A broad
         classification of "ends" used during winding in which the
         filaments are not twisted.  A "strand," which is the most
         common form of roving delivered from a spool to a winding,
         is a grouping of "ends" (ranging from one to sixty ends
         per strand).  An "end" is a grouping of generally 204
         single filaments.  In general, roving is the smallest
         unit dispensed from a spool to a mandrel.


A-21

saw-tooth  -  Notched sections used to stabilize fiber bands
(see Figure 5B).

winding angle (helix angle)  -  See "angle" and Figure A-6.

1800-yield  -  A measure of roving which specifies the length
per pound of an equivalent single filament; that is,
an 1800-yield roving would yield a single filament
1800 yards long for each pound of roving.